

ν_e Appearance Searches for Light Sterile Neutrinos



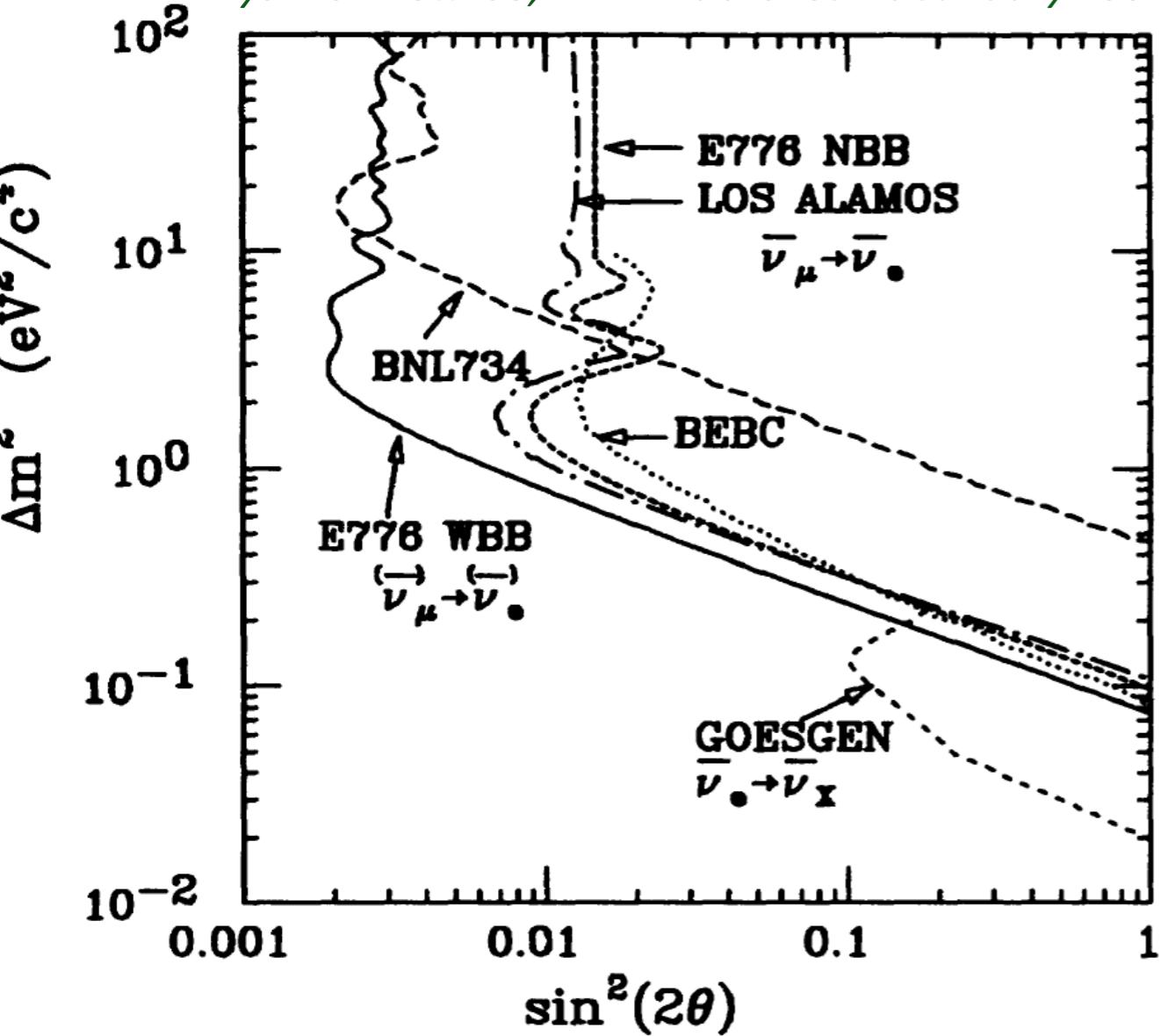
Alexandre Sousa
University of Cincinnati

Workshop on the
Intermediate Neutrino Program

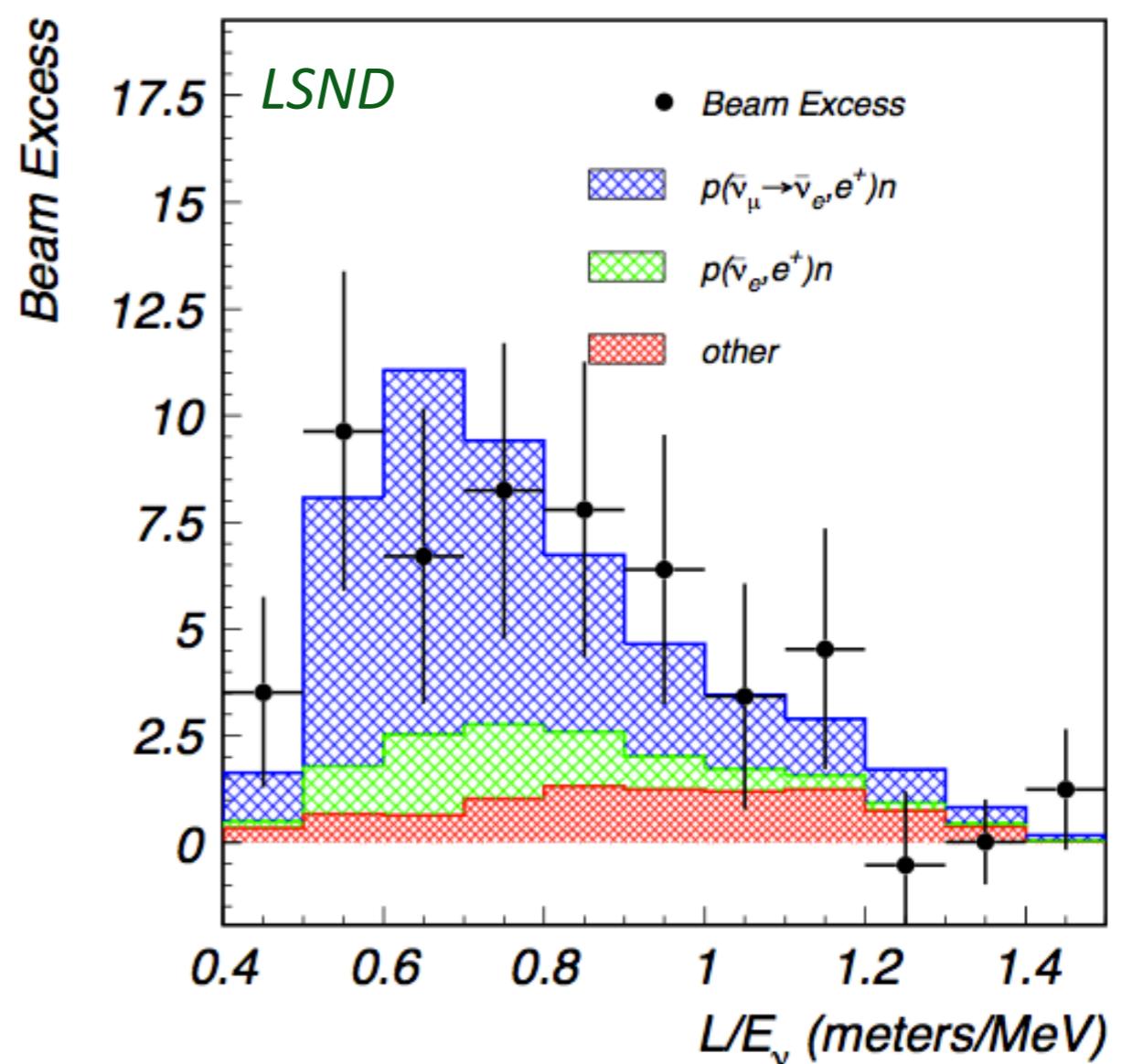
Brookhaven National Laboratory, Feb. 5, 2015

Current ν_e Appearance Results

Phys. Rev. Lett. 68, 274 – Published 20 January 1992



Phys. Rev. D 64, 112007 (2001)

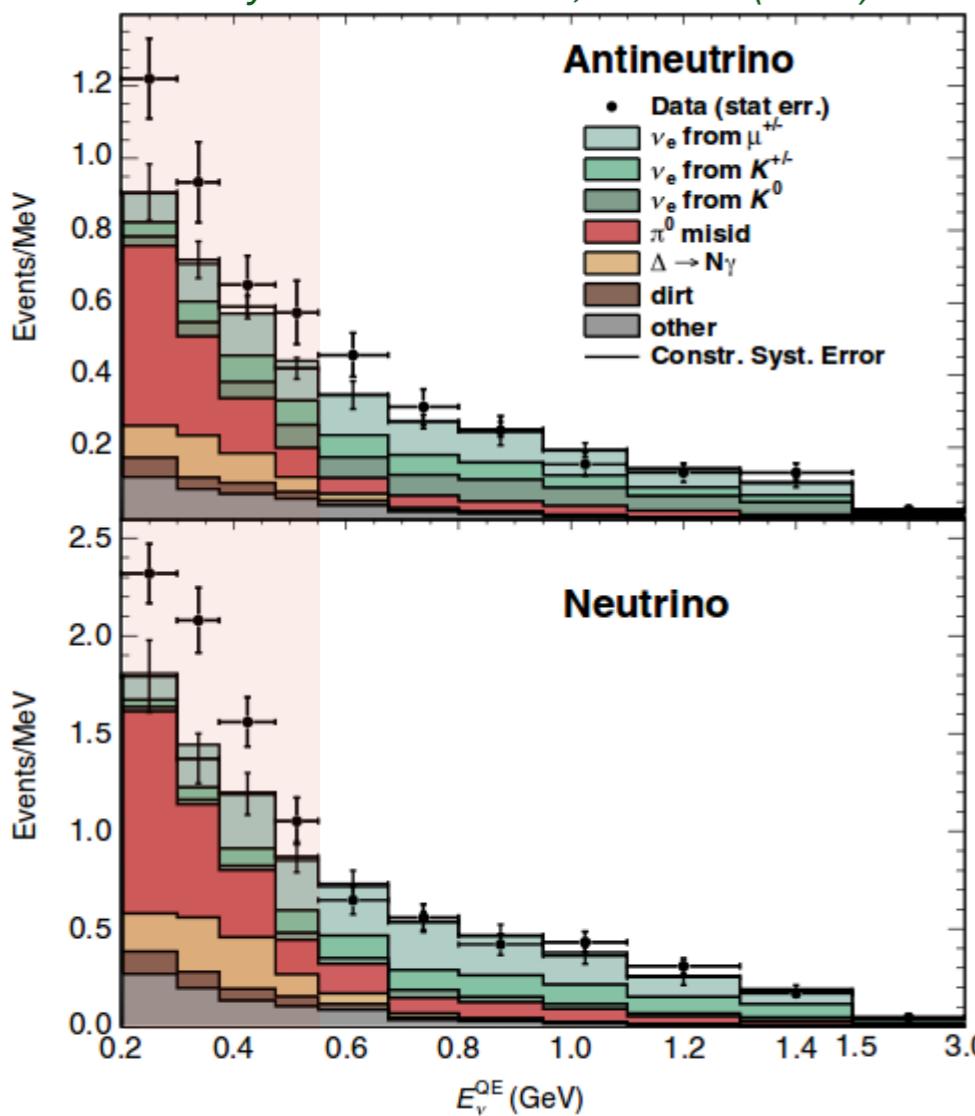


- In 1992, E776 at BNL had the strongest limits on ν_e , $\bar{\nu}_e$ appearance

- Strongest indication (3.8σ) of large Δm^2 oscillations from LSND $\bar{\nu}_e$ excess in $\bar{\nu}_\mu$ beam
- 167 ton liquid scintillator detector exposed to decay-at-rest (DAR) beam with a 30 m baseline
- No excess seen by KARMEN

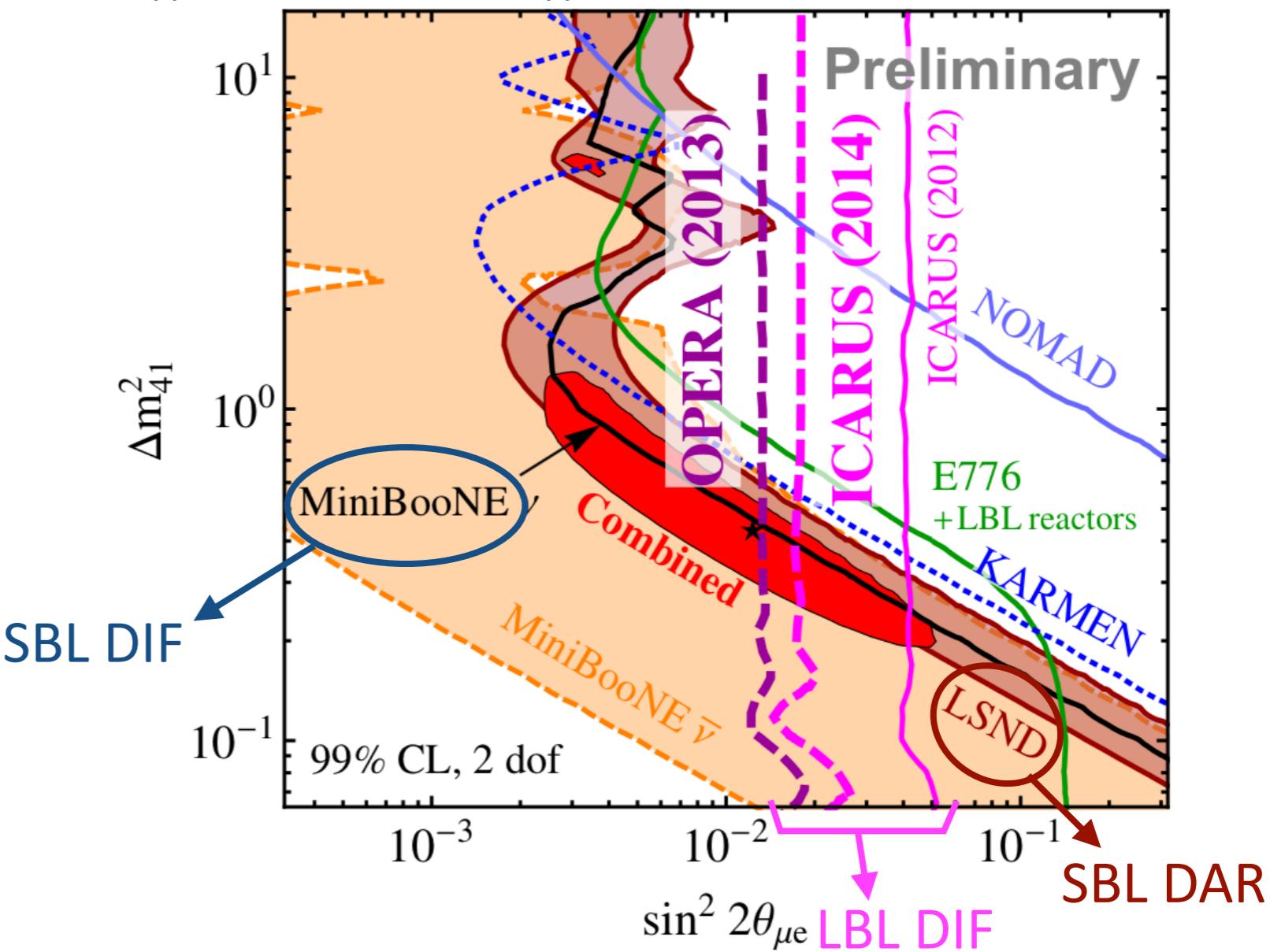
Current v_e Appearance Results

Phys. Rev. Lett. 110, 161801 (2013)



- ▶ MiniBooNE saw a low-energy excess in both neutrino and antineutrino running
 - ▶ 806 ton liquid scintillator detector exposed to decay-in-flight (DIF) beam with a 541 m baseline

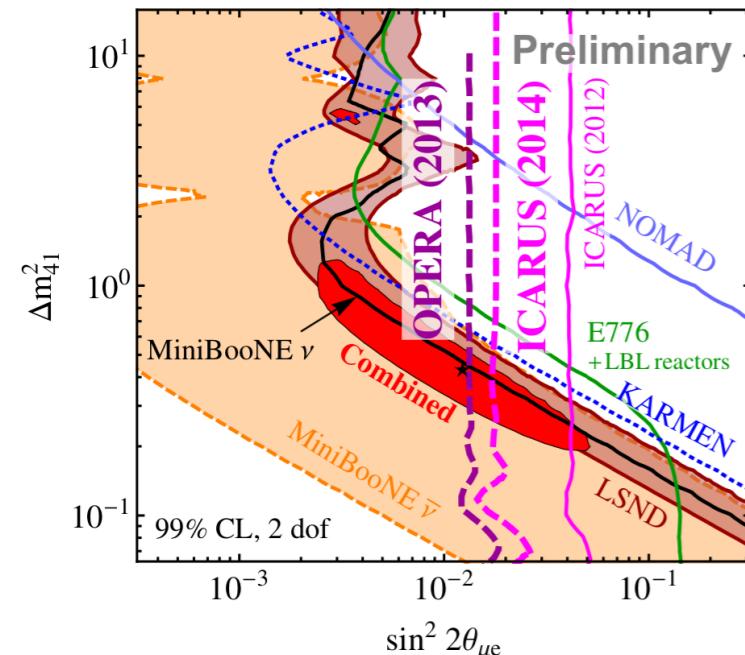
J. Kopp, Neutrino 2014, and Kopp, Machado, Maltoni, Schwetz, arXiv:1303.3011



Experiments	Neutrino source	signal	type	Significance σ
LSND	μ Decay-At-Rest	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	appearance	3.8
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	appearance	3.4
		$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	appearance	2.8

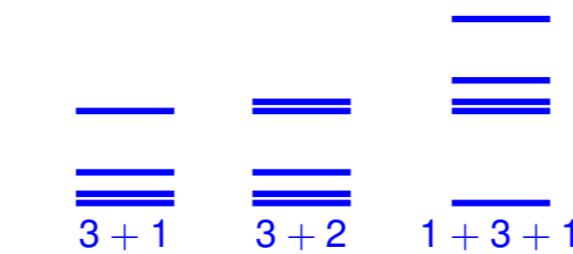
Current ν_e Appearance Results

J. Kopp, Neutrino 2014, and Kopp, Machado, Maltoni, Schwetz, arXiv:1303.3011



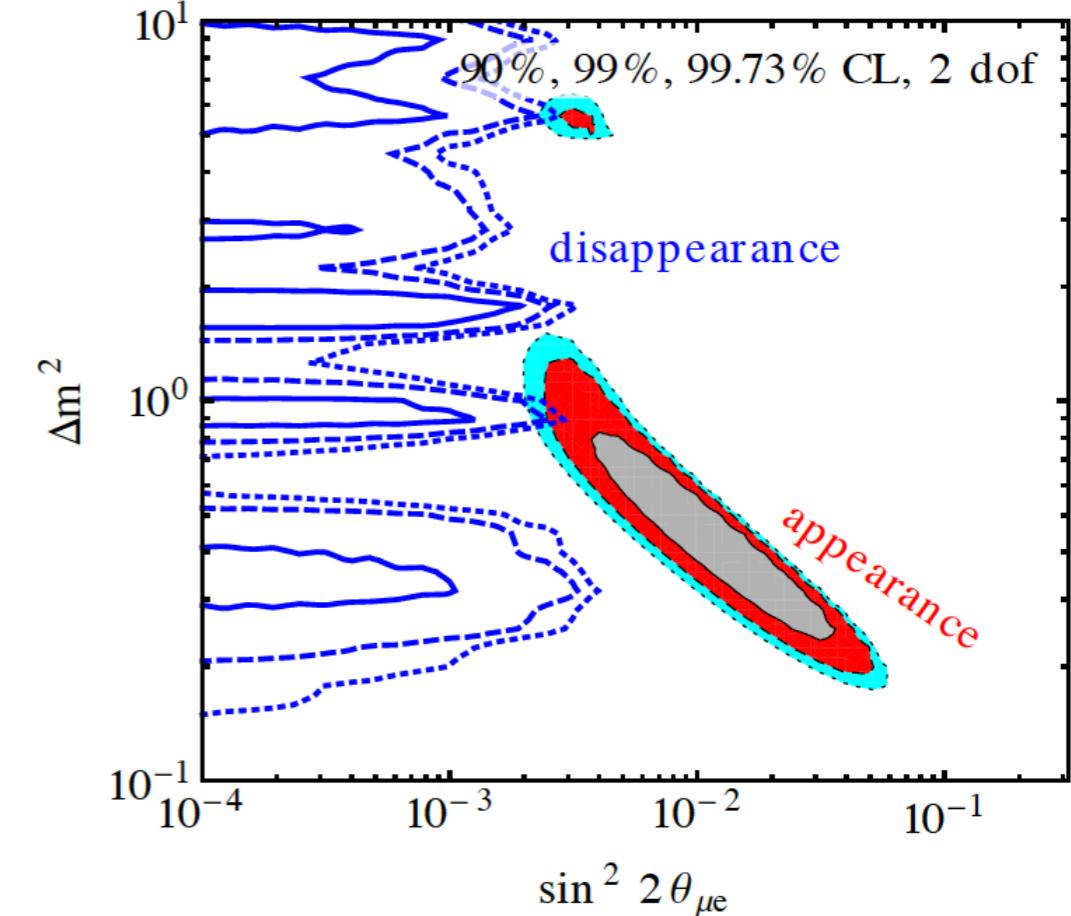
	χ^2_{3+1}/dof	χ^2_{3+2}/dof	$\chi^2_{1+3+1}/\text{dof}$
LSND	11.0/11	8.6/11	7.5/11
MiniB ν	19.3/11	10.6/11	9.1/11
MiniB $\bar{\nu}$	10.7/11	9.6/11	12.7/11
E776	32.4/24	29.2/24	31.3/24
KARMEN	9.8/9	8.6/9	9.0/9
NOMAD	0.0/1	0.0/1	0.0/1
ICARUS	2.0/1	2.3/1	1.5/1
Combined	87.9/66	72.7/63	74.6/63

- Global fit to all appearance data is consistent
- Background oscillations important in MiniBooNE and E776
- Significant improvement in $3+2$ and $1+3+1$



JK Machado Maltoni Schwetz, 1303.3011
see also fits by Giunti Laveder et al.

Conrad Ignarra Karagiorgi Shaevitz Spitz Djurcic Sorel



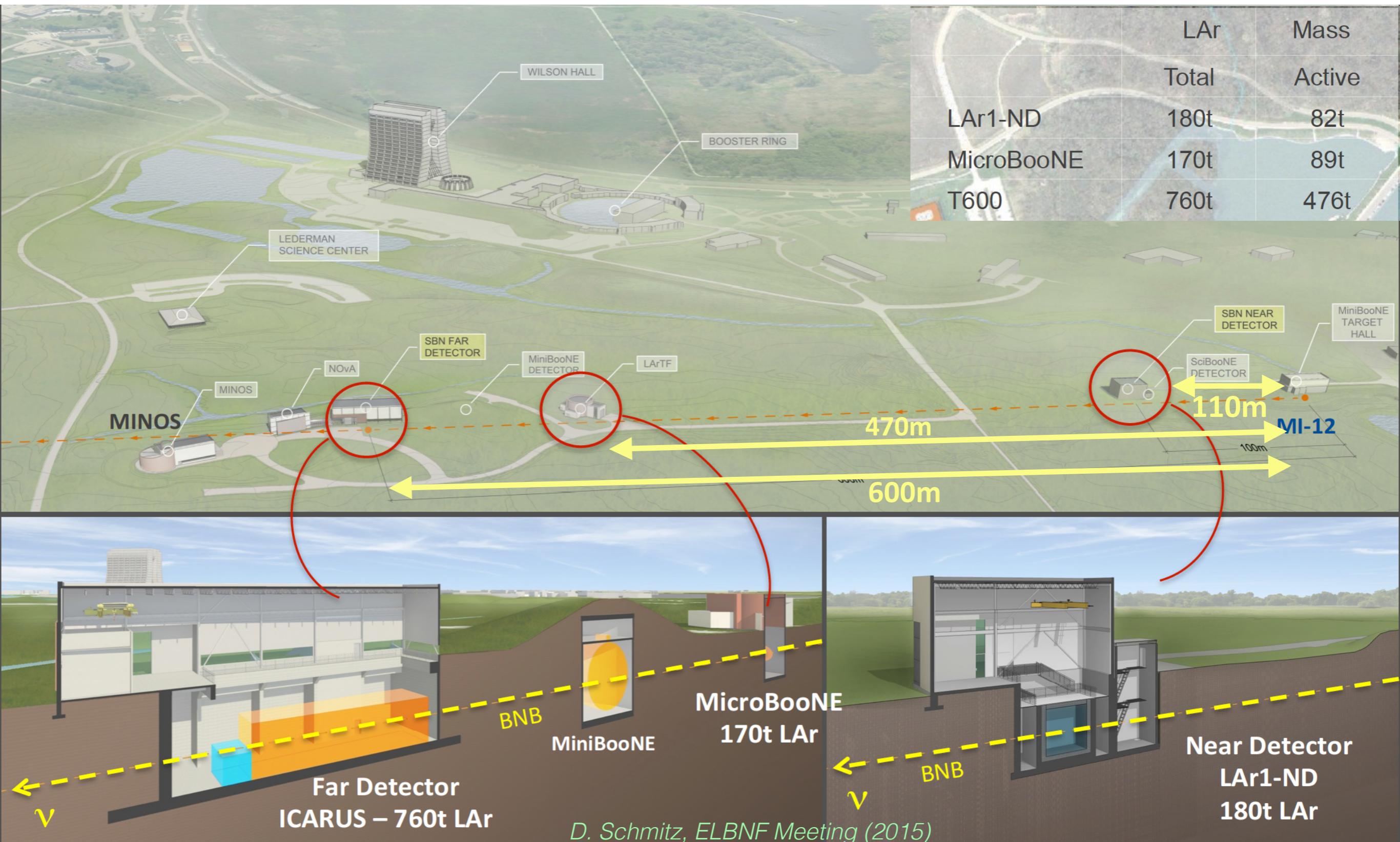
- ▶ Appearance data consistent with sterile neutrino mixing
- ▶ However, there is tension with null disappearance results (see André's talk)
- ▶ See next talks by Randy Johnson and Janet Conrad on $\nu_e, \bar{\nu}_e$, and $\nu_\mu, \bar{\nu}_\mu$ disappearance

Outline

- ▶ Short-Baseline Decay-In-Flight
- ▶ Short-Baseline Decay-At-Rest
- ▶ Short-Baseline Muon Decay-In-Flight - nuSTORM
- ▶ Long-Baseline Decay-in-Flight
- ▶ Summary and Conclusions

SBL Decay-In-Flight - SBN

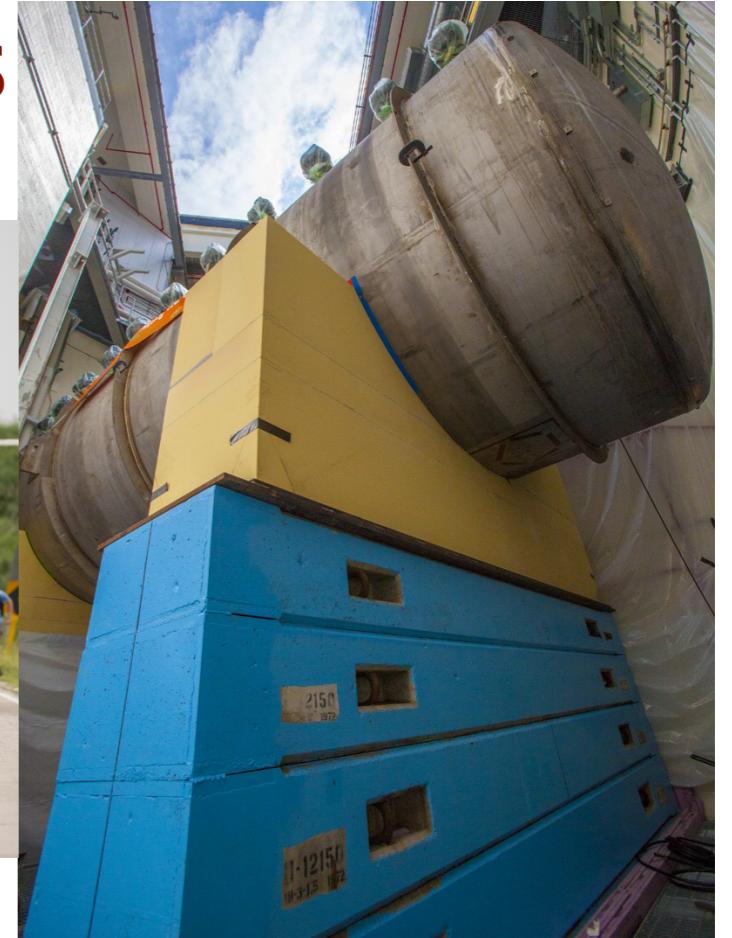
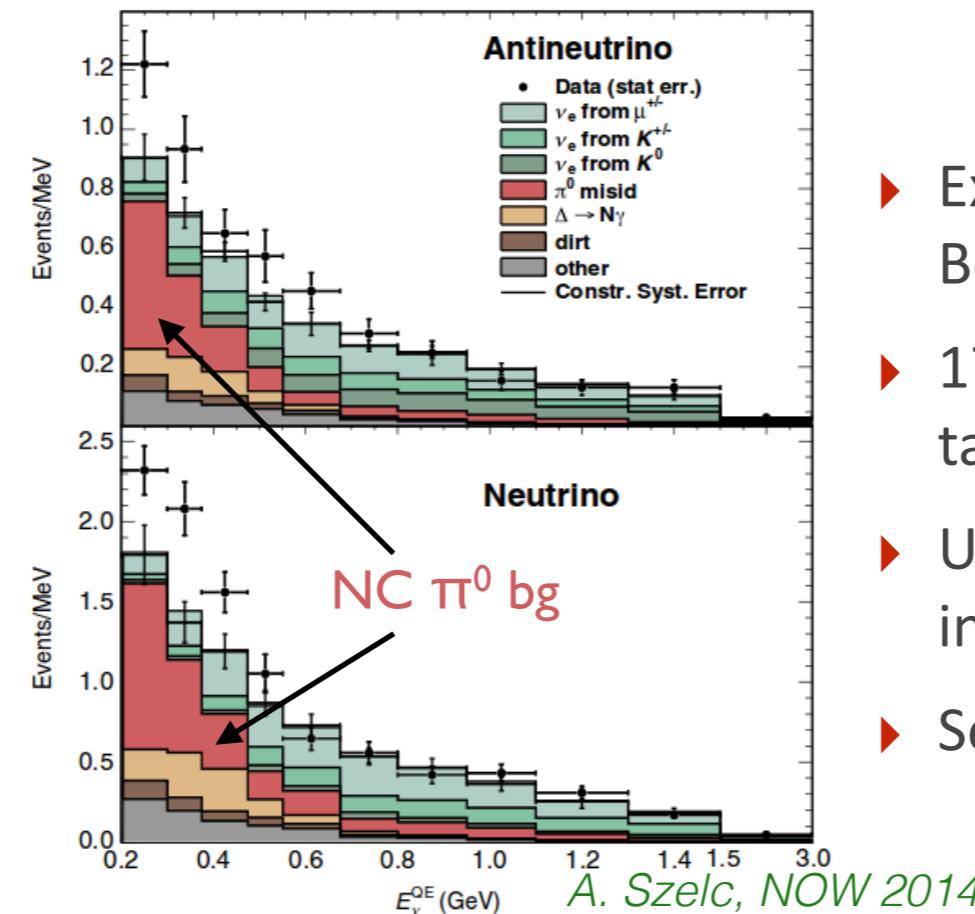
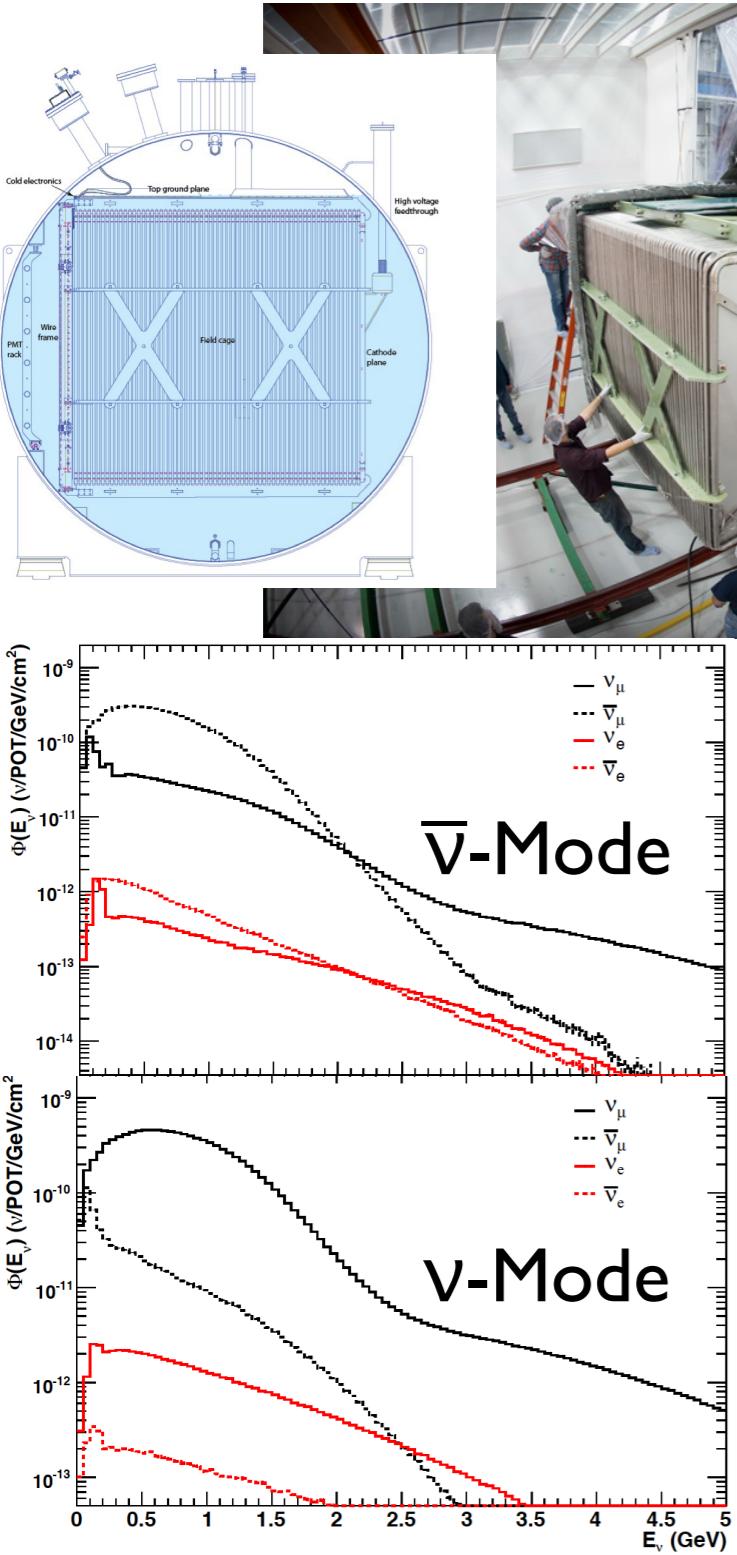
- Short-Baseline Neutrino Program @ Fermilab, US



SBL Decay-In-Flight - MicroBooNE

Short-Baseline Neutrino Program @ Fermilab, US

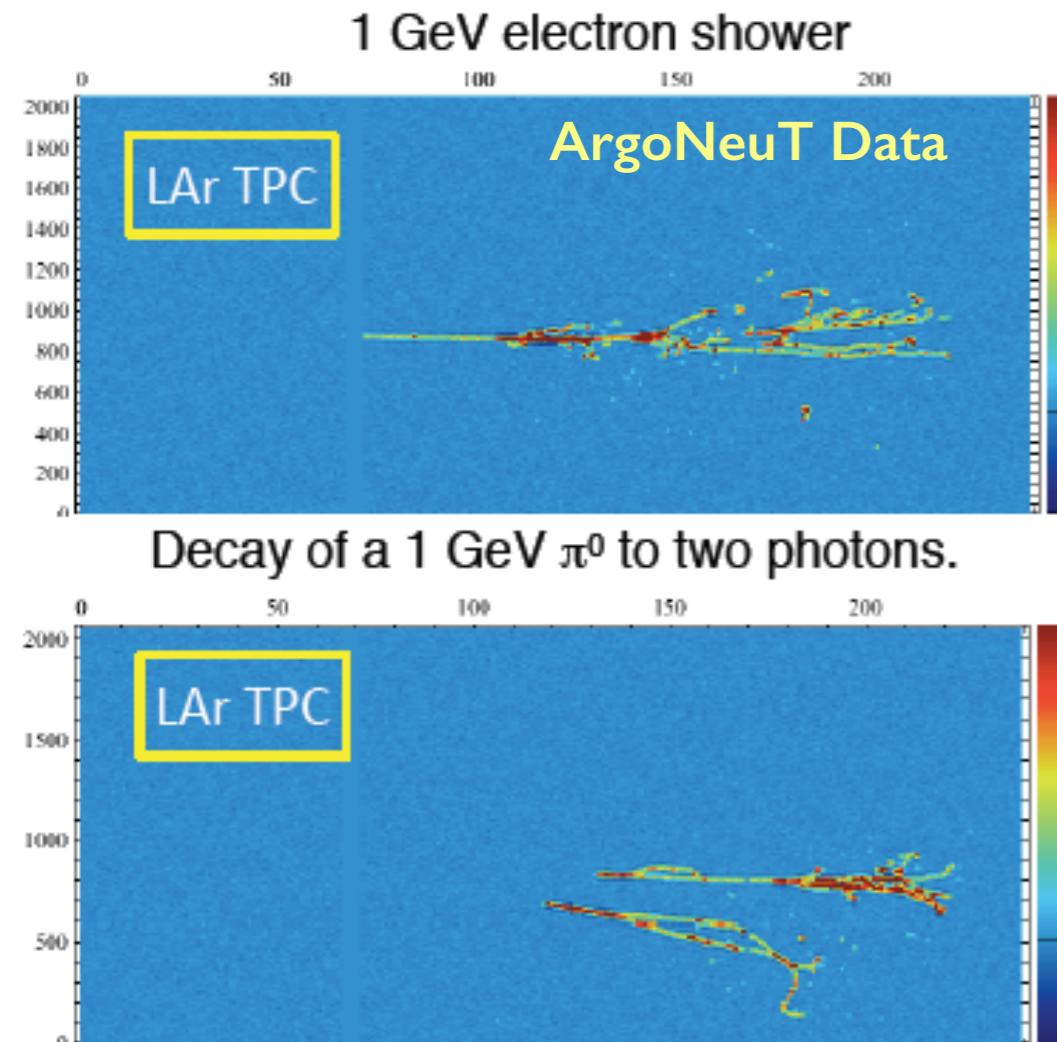
► MicroBooNE will be taking data soon!



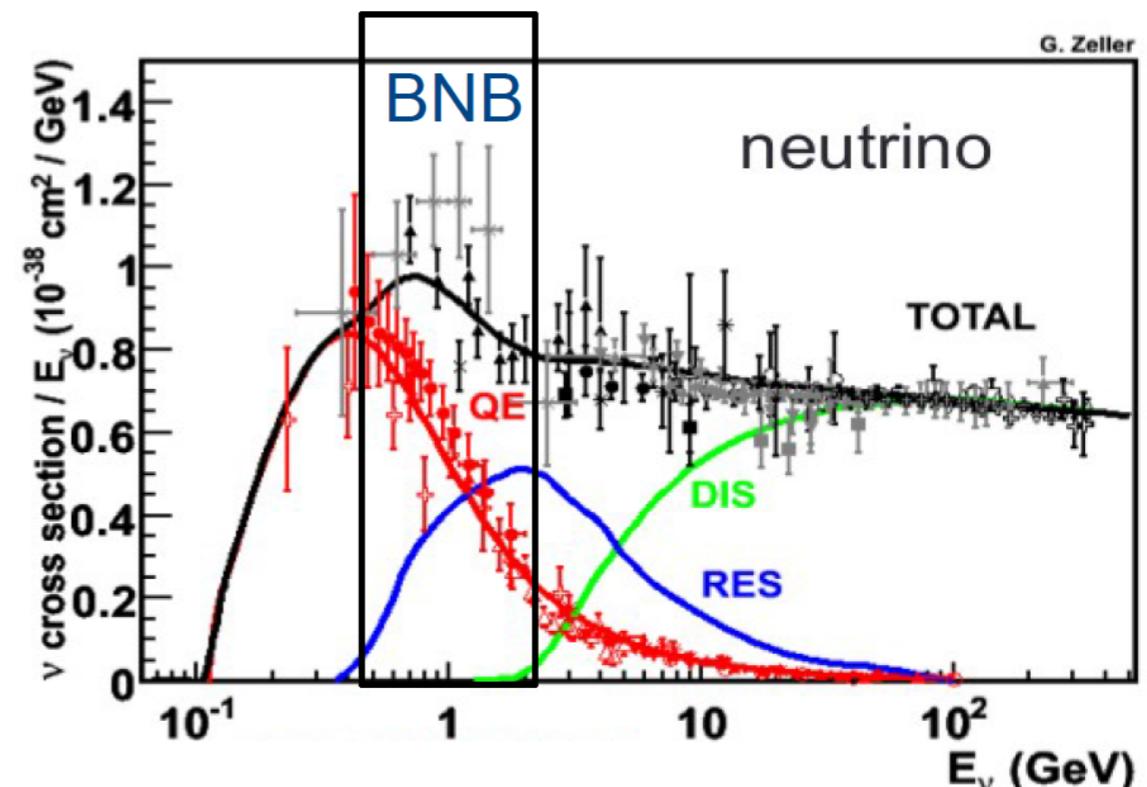
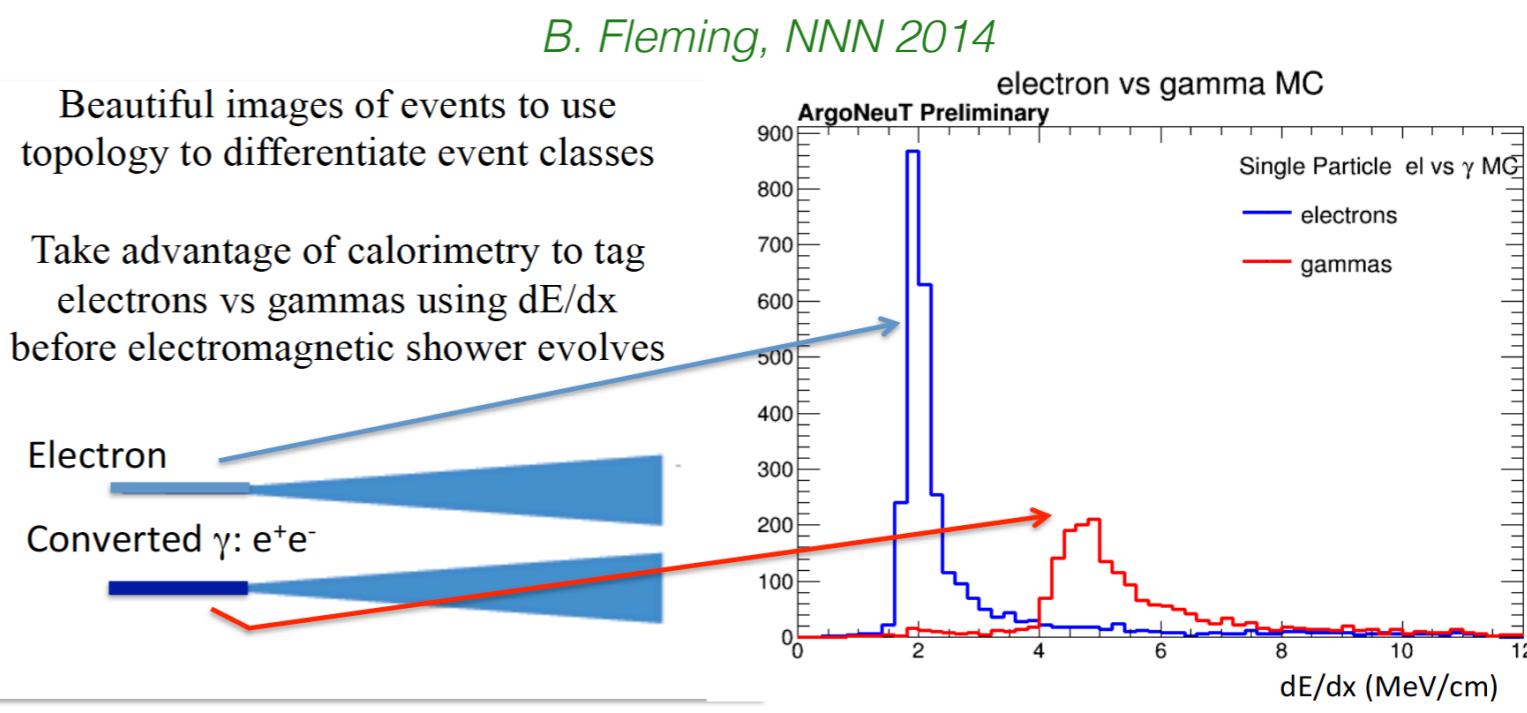
- Exposed to pion decay-in-flight Booster neutrino beam (BNB)
- 170 t LAr detector, 470 m from BNB target
- Understand low-energy excess seen in MiniBooNE
- Search for SBL neutrino oscillations

SBL Decay-In-Flight - MicroBooNE

- Short-Baseline Neutrino Program @ Fermilab, US



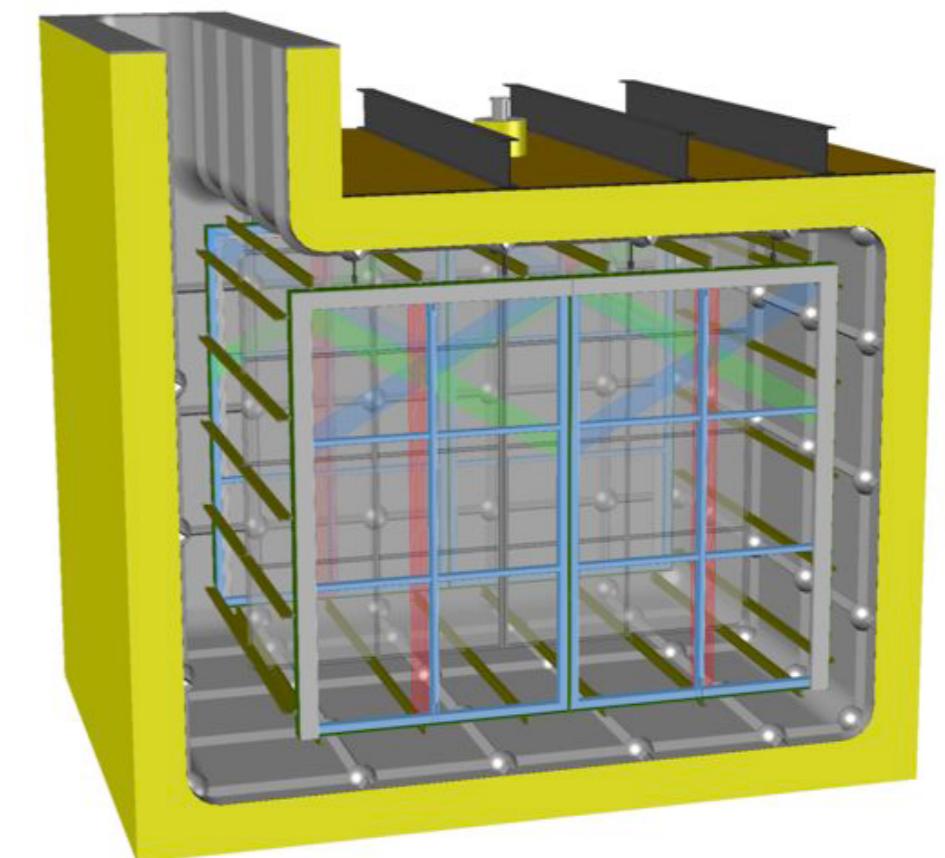
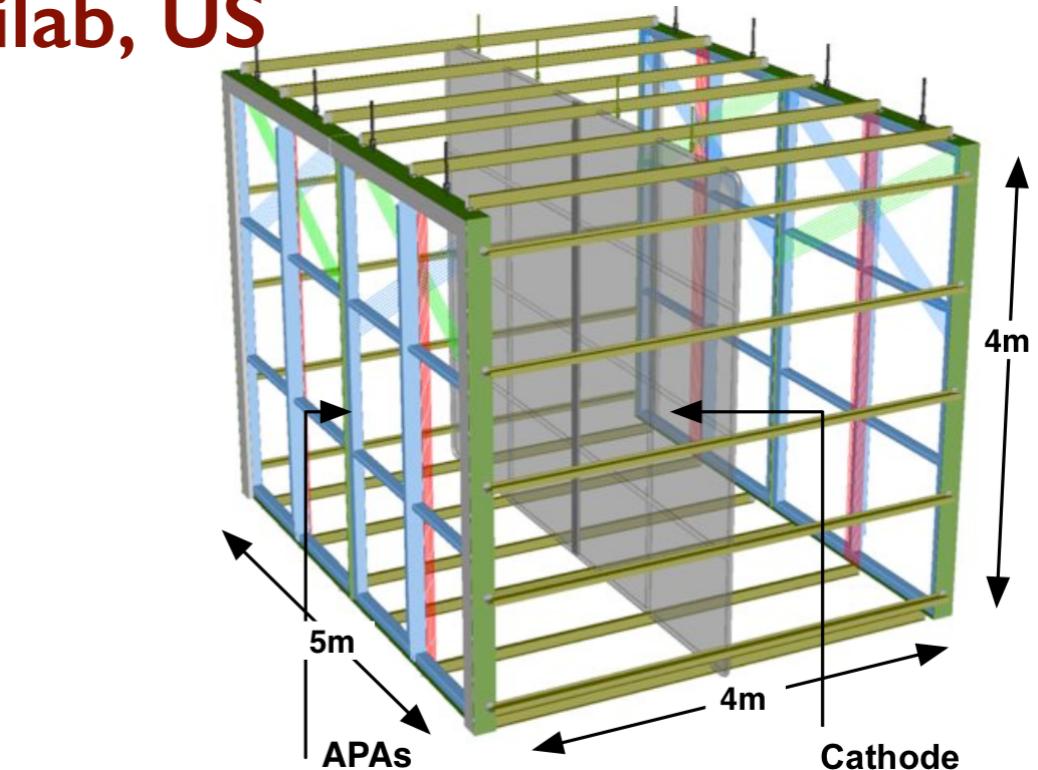
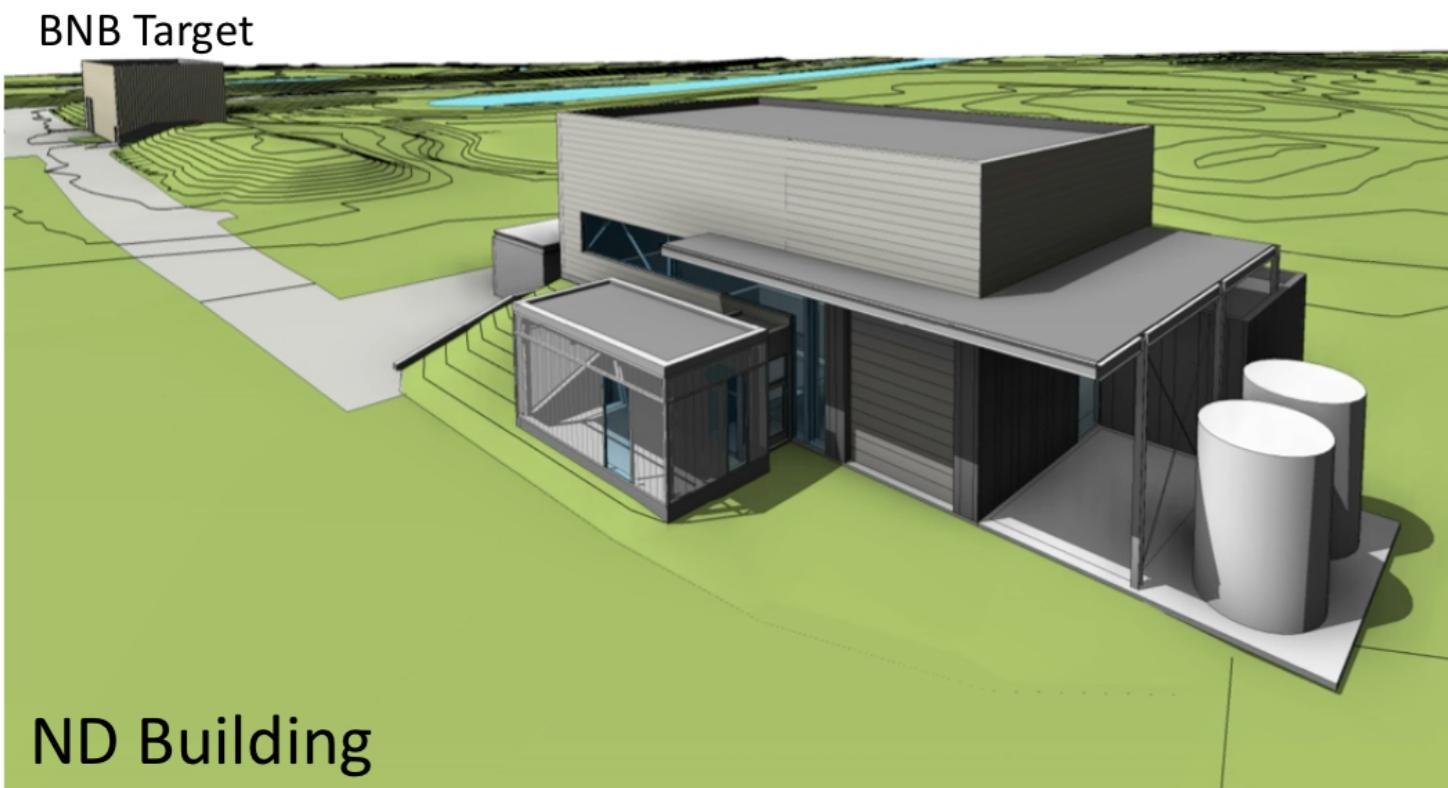
- ▶ LAr technology allows excellent separation between electron and gamma showers using topology and dE/dx
- ▶ Will make measurement of cross-sections in LAr, important for future LAr-based experiments, e.g. ELBNF
- ▶ Detector operations starting in May 2015!



SBL Decay-In-Flight - LAr1-ND

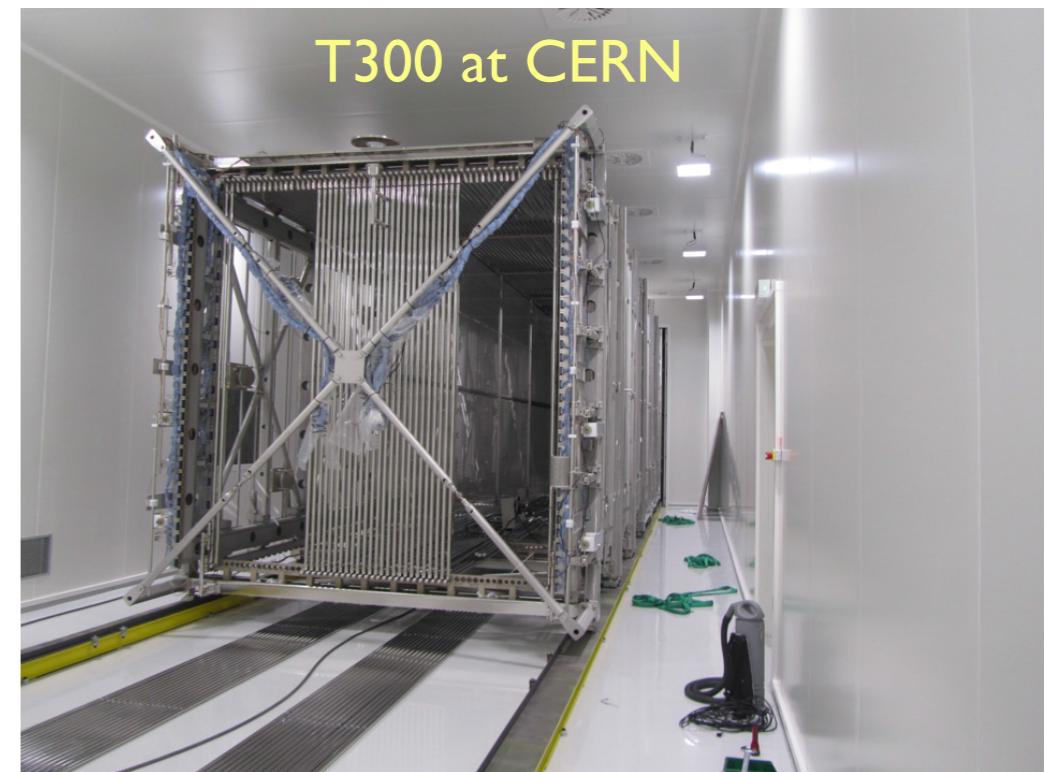
- **Short-Baseline Neutrino Program @ Fermilab, US**

- ▶ 180 ton LAr TPC placed 100-150 m from BNB target
- ▶ Leverages experience from ICARUS ArgoNeuT, MicroBooNE, LBNE 35 ton.
- ▶ Follows LBNE TPC design
- ▶ In R&D phase following approval in Summer 2014



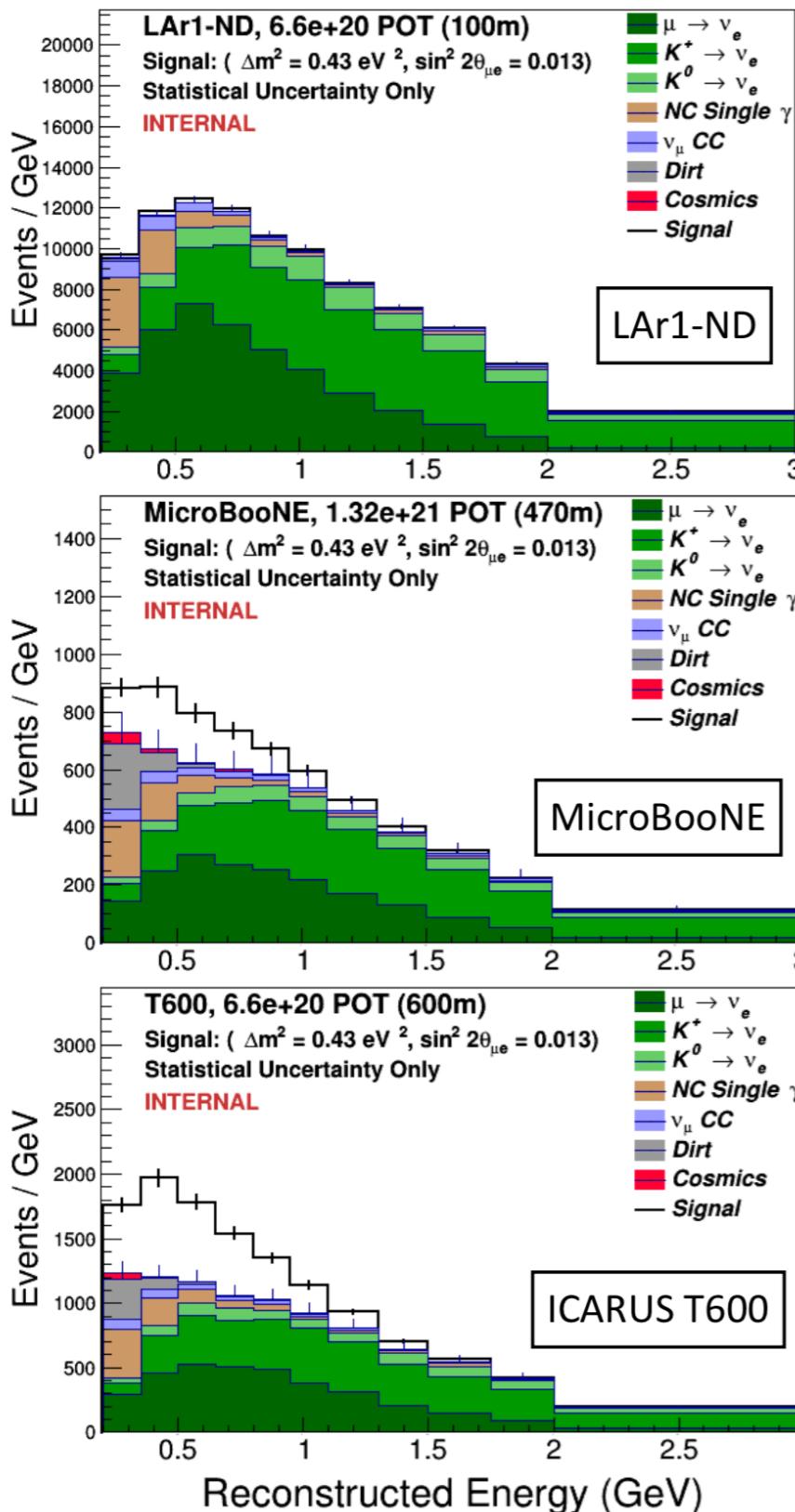
SBL Decay-In-Flight - ICARUS

- **Short-Baseline Neutrino Program @ Fermilab, US**
 - ▶ ICARUS-T600 is the largest LAr TPC built to date
 - ▶ ICARUS-W104 approved at CERN to refurbish T600 with new cryostats, improved light collection and electronics
 - ▶ Planning to move T600 to Fermilab in 2017, after completion of SBN FD building



SBL Decay-In-Flight - SBN

- Short-Baseline Neutrino Program @ Fermilab, US



- ▶ SBN expected Signal and Backgrounds - ν mode
- ▶ Dominant background from intrinsic beam ν_e (0.5% of beam)

- ❖ Electron neutrino CC interactions

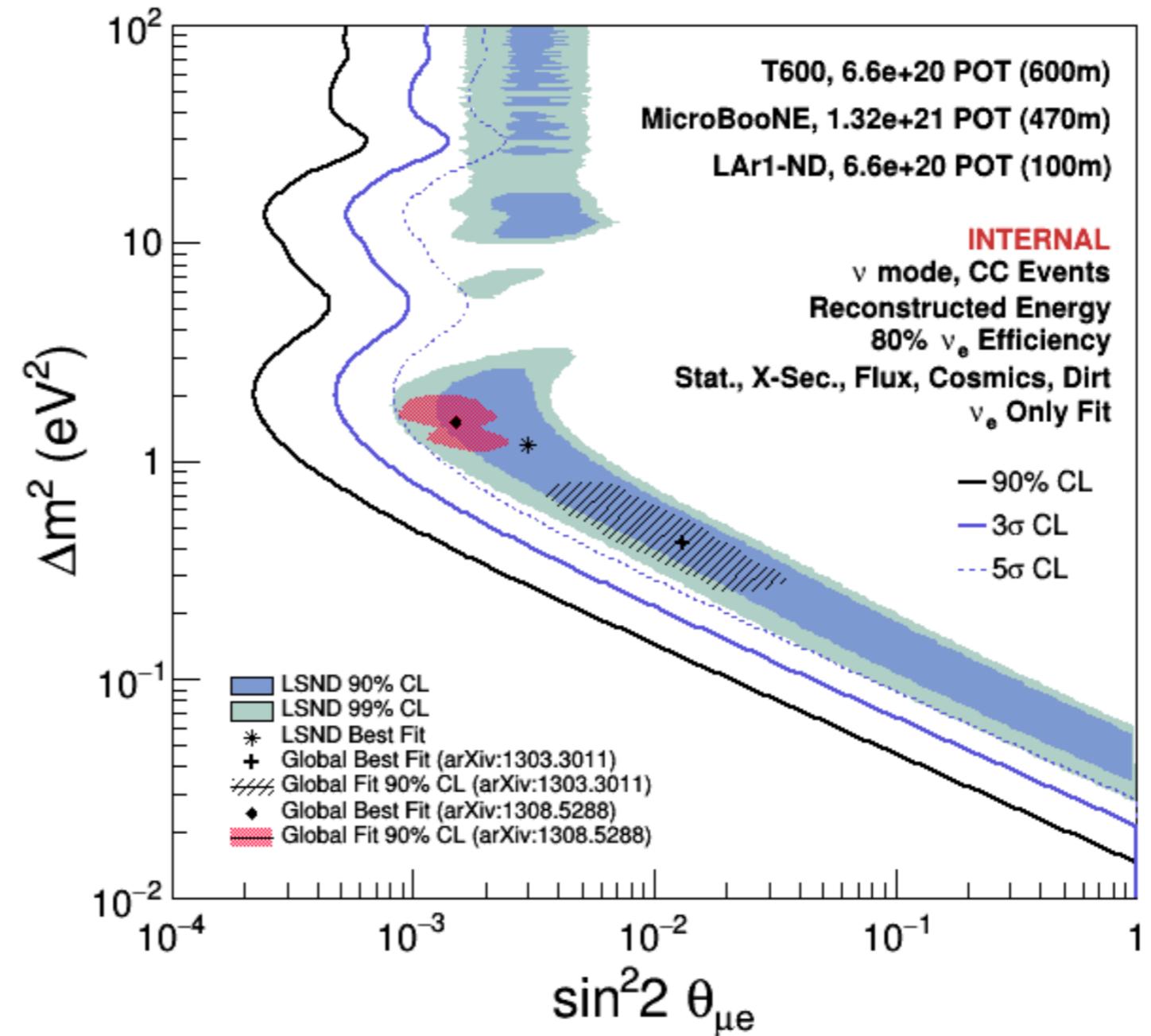
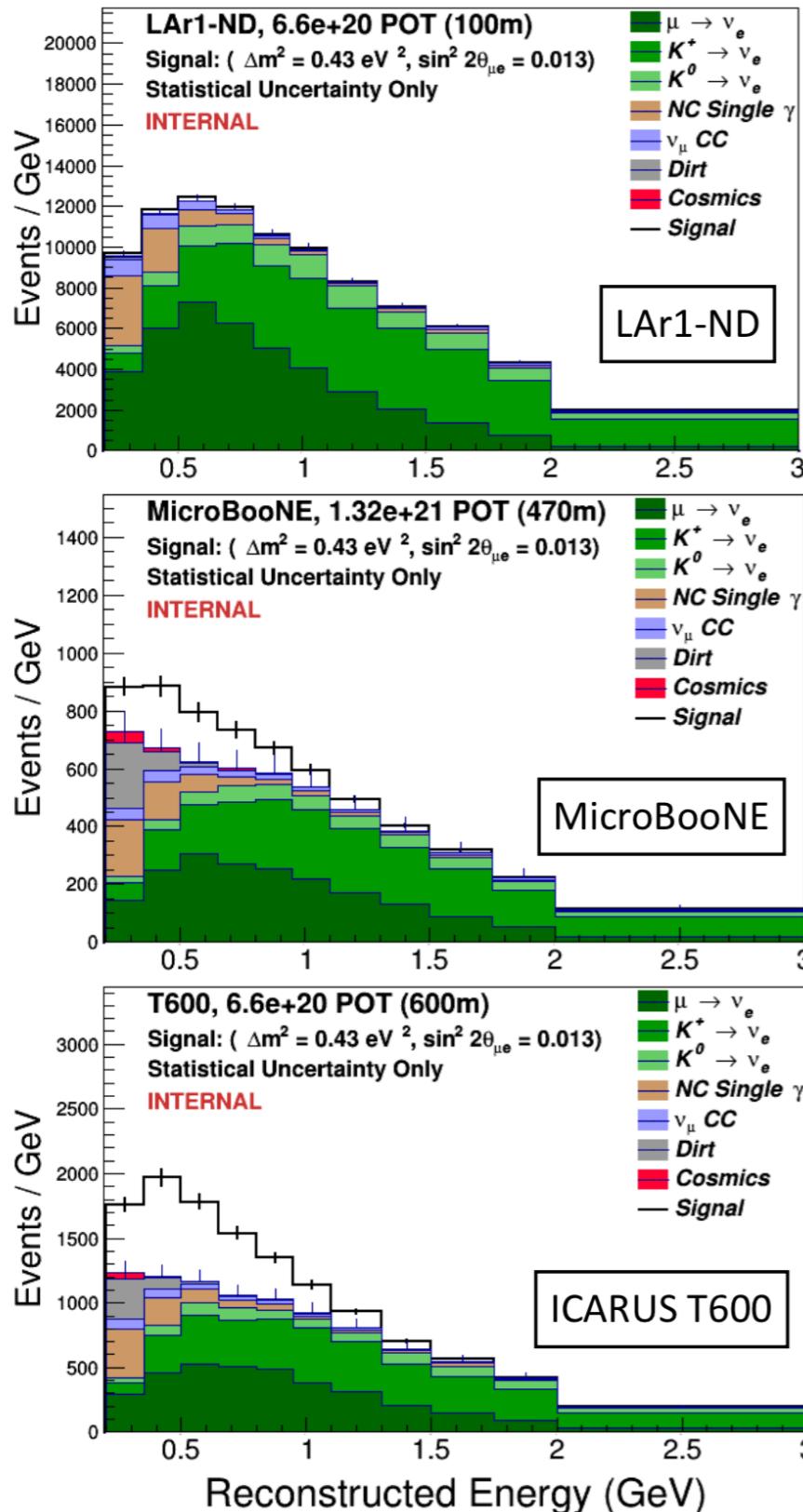
- $\pi \rightarrow \mu \rightarrow \nu_e$
- $K^+ \rightarrow \nu_e$
- $K^0 \rightarrow \nu_e$
- Sample appearance signal

- ❖ Photon-induced e.m. shower backgrounds

- NC misIDs
- $\nu_\mu CC$ misIDs
- “Dirt” Backgrounds: beam-related but out-of-detector interactions
- Cosmogenic photon sources

SBL Decay-In-Flight - SBN

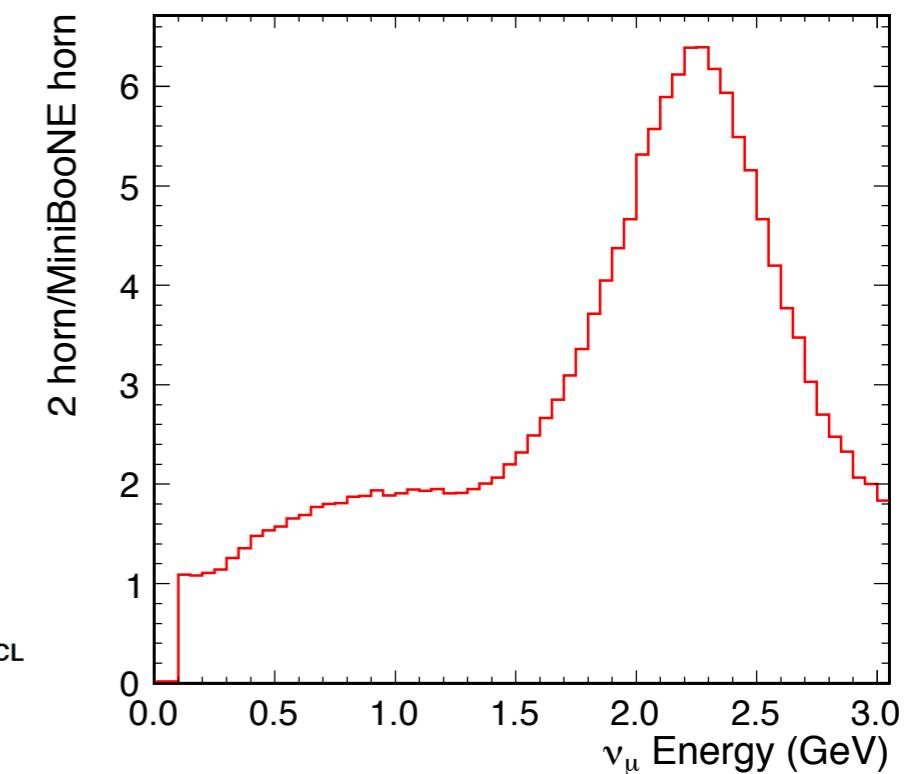
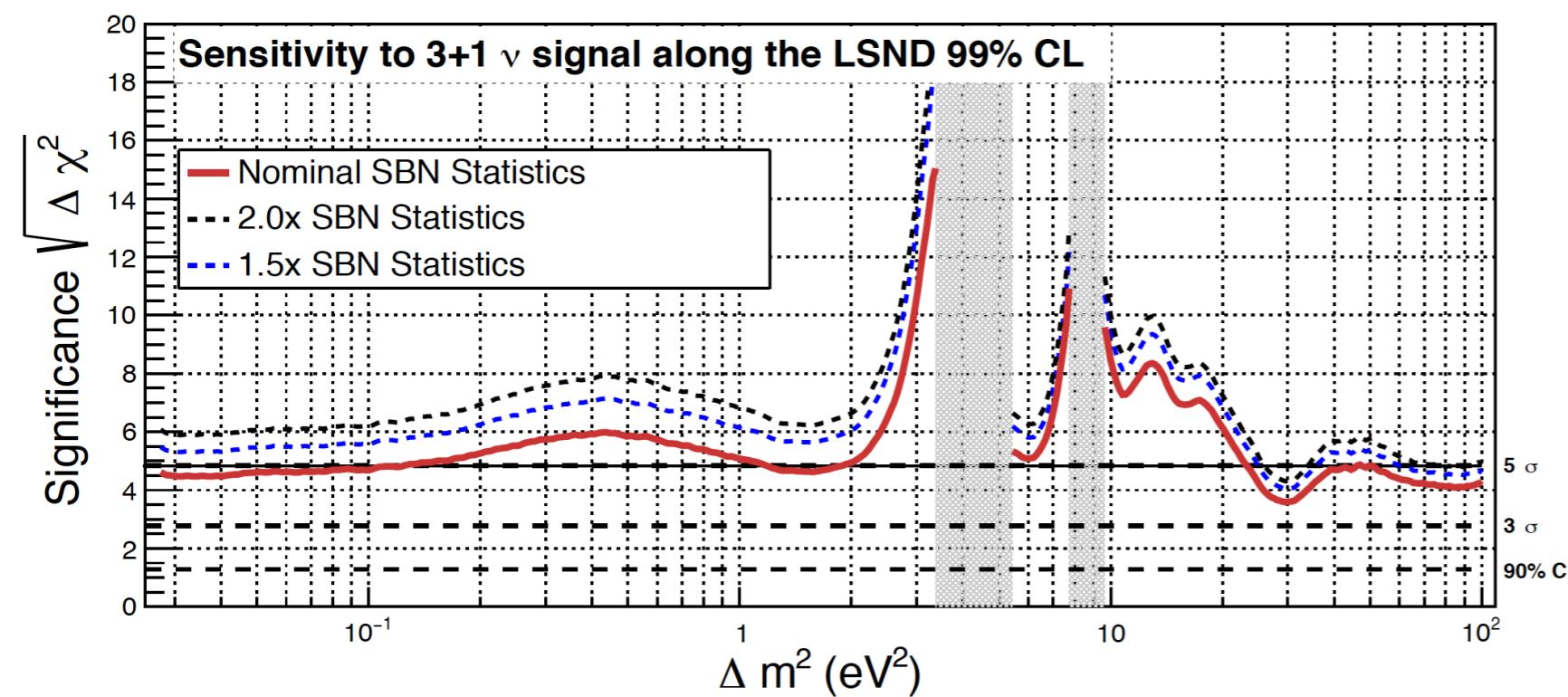
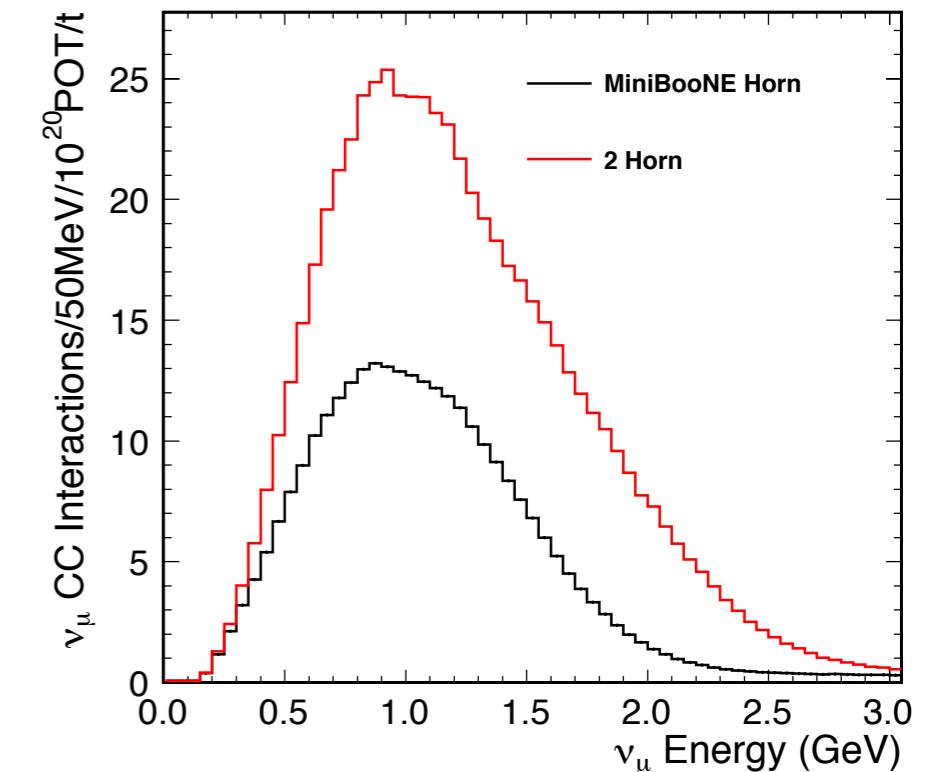
- Short-Baseline Neutrino Program @ Fermilab, US



► SBN ν_e appearance sensitivity - ν mode

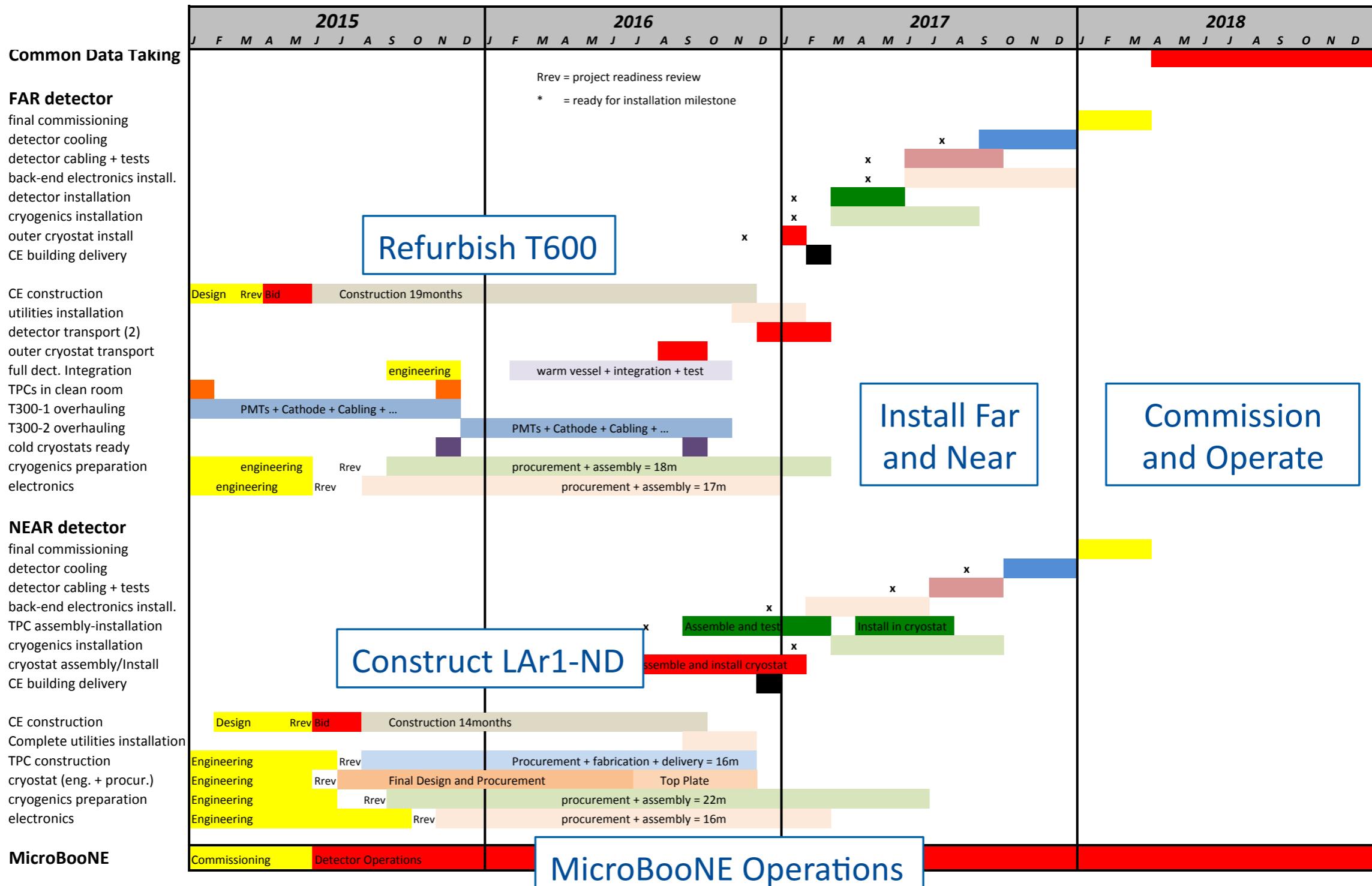
SBL Decay-In-Flight - BNB+

- Short-Baseline Neutrino Program @ Fermilab, US
 - ▶ Upgrade BNB with second horn
 - ▶ May increase statistics by a factor of 2
 - ▶ Main costs in new horn(s), power supplies and collimators
 - ▶ Detailed cost and schedule estimates needed to assess feasibility



SBL Decay-In-Flight - SBN

- Short-Baseline Neutrino Program @ Fermilab, US



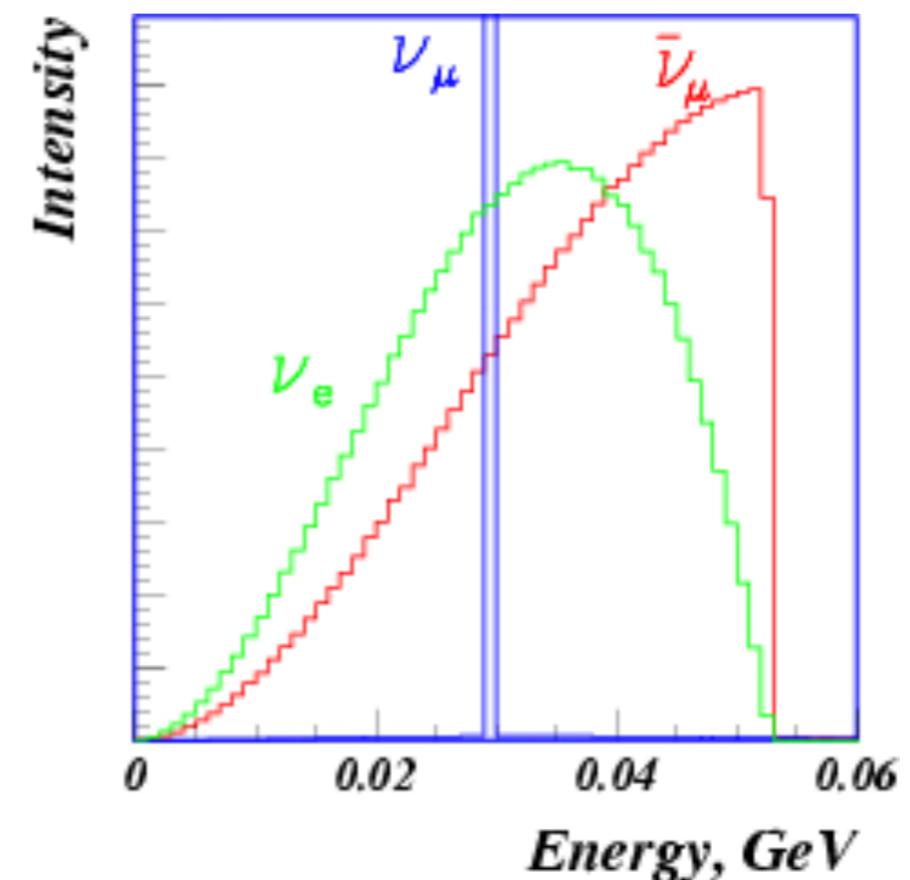
► SBN Program Schedule

P. Wilson, WINP 2015

SBL Decay-At-Rest - OscSNS

- **OscSNS (Oscillations at the Spallation Neutron Source), at Oak Ridge Nat. Lab, US**
- ▶ Direct test of LSND with a more intense and well understood pion, muon decay-at-rest beam (1.3 GeV protons on Hg target) with 1.4 MW
- ▶ SNS operates short-pulsed beam, 695 ns spill, 60 Hz rep rate
 - ▶ 2.2×10^{23} protons/year $\Rightarrow 2.8 \times 10^{22}$ v/year
- ▶ Use MiniBooNE-like detector with same type of liquid scintillator as LSND, but faster electronics (200 MHz vs 10 MHz)

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ \nu_\mu, & \tau &= 26 \text{ ns} \\ \mu^+ &\rightarrow e^+ \bar{\nu}_\mu \nu_e, & \tau &= 2.2 \mu\text{s} \\ E_{\nu_\mu} &= 29.8 \text{ MeV}\end{aligned}$$

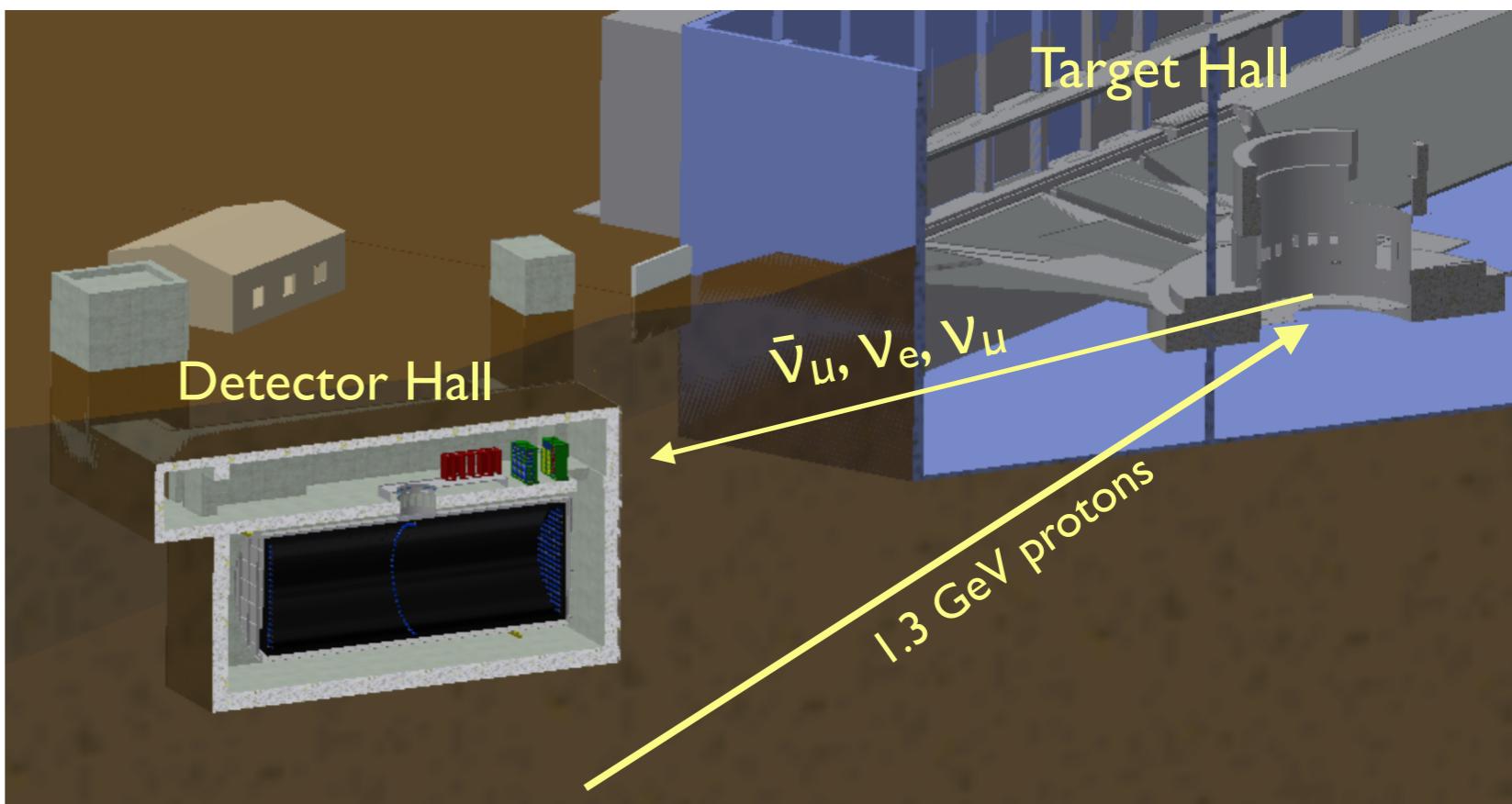


arXiv:1307.7097

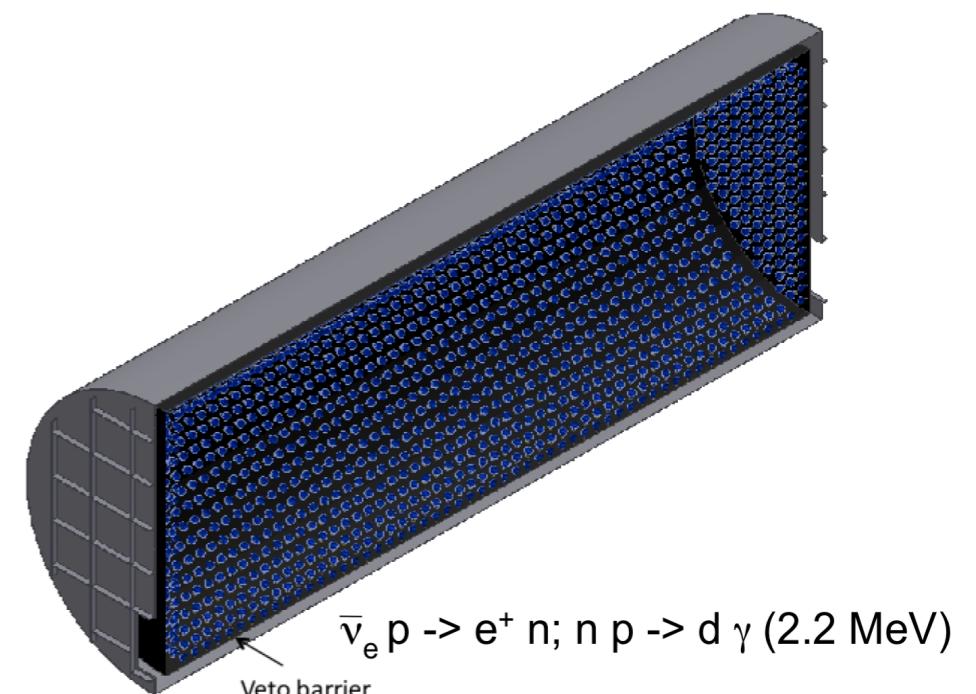
SBL Decay-At-Rest - OscSNS

- OscSNS (Oscillations at the Spallation Neutron Source), at Oak Ridge Nat. Lab, US

- ▶ Place detector 60 m upstream of Hg target dump, at 150° angle
 - Decay-in-flight backgrounds negligible
- ▶ 6 m of dirt overburden to shield cosmics and beam-induced neutrons



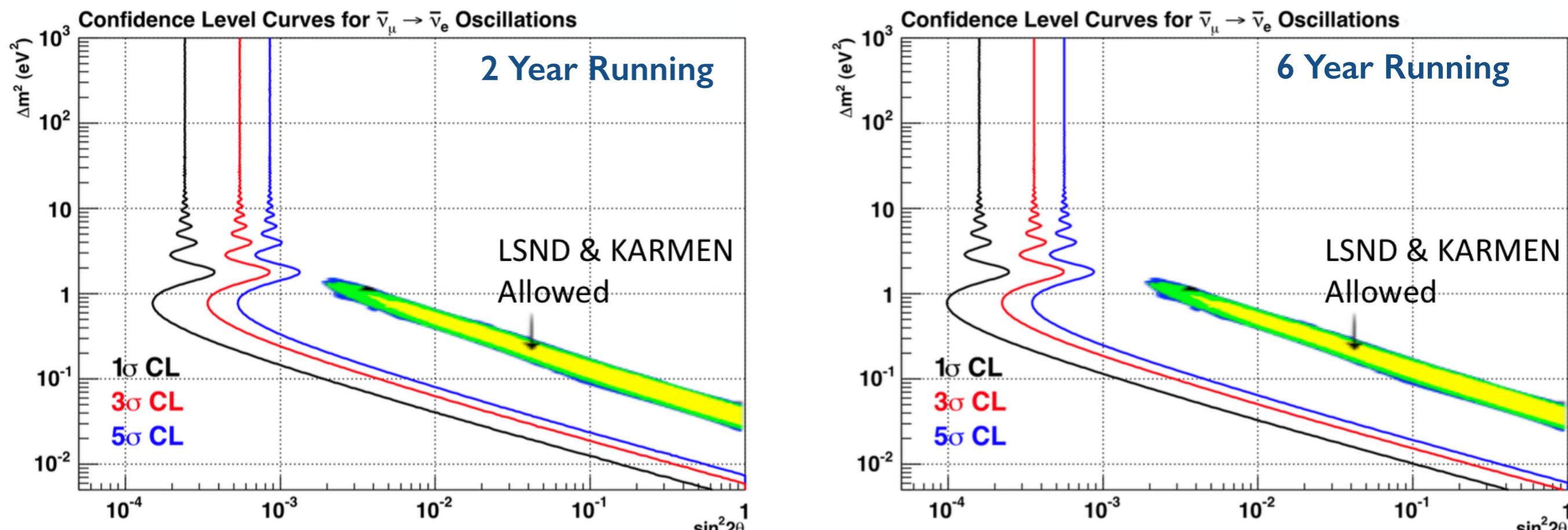
- ▶ Detector with similar design to MiniBooNE, with higher PMT coverage (25%)
 - 886 ton (450 ton fiducial), 20.5 m long, 8.0 m diameter
 - 4290 8-inch PMTs
 - Butyl-PBD added to mineral oil to improve light output of low-energy particles and enable neutron detection
 - Also considering Gd-doped scintillator



SBL Decay-At-Rest - OscSNS

- **OscSNS (Oscillations at the Spallation Neutron Source), at Oak Ridge Nat. Lab, US**
- ▶ Look for appearance signal in $\bar{\nu}_\mu$ from muon decay and ν_μ from pion decay
 - **0.1% intrinsic $\bar{\nu}_e$ in beam** as π^- , μ^- and are captured in target; timing cut => x2 reduction in BG
 - Showing expected Signal and BG yields for 1 year of OscSNS running assuming 50% detector efficiency, 50% beam-on efficiency
- ▶ 5 σ sensitivity after 2 years fully includes allowed region from LSND and KARMEN combined fit

Channel	Background	Signal
Appearance Search		
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e: \bar{\nu}_e \ ^{12}C \rightarrow e^+ \ ^{11}B \ n$		
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e: \bar{\nu}_e \ p \rightarrow e^+ \ n$	42 ± 5	120 ± 10
$\nu_\mu \rightarrow \nu_e: \nu_e \ ^{12}C \rightarrow e^- \ ^{12}N_{gs}$	12 ± 3	3.5 ± 1.5



SBL Decay-At-Rest - OscSNS

- **OscSNS (Oscillations at the Spallation Neutron Source), at Oak Ridge Nat. Lab, US**
- ▶ Budgeting \$20 million for project (~\$15 million civil construction, ~\$5 million detector)
- ▶ From OscSNS White Paper (arXiv:1307.7097):
 - Visit SNS, present physics plan. (done: April 12, 2013)
 - Attend Snowmass, garner support from the community. (done)
 - Obtain letter of support from SNS management and have it sent to DOE. (done)
 - Submit R&D proposals to DOE for the following ground work (Fall, 2013):
 - design new electronics
 - test oil and scintillators from various sources
 - develop simulations for the main detector, including reconstruction and particle ID algorithms
 - develop improved neutrino flux simulations
 - Submit white paper to DOE.
- ▶ Projecting 3 years from ground breaking to project completion

SBL Decay-At-Rest - P56@MLF

- P56 @ J-PARC-MLF (Materials and Life Science Facility), Japan

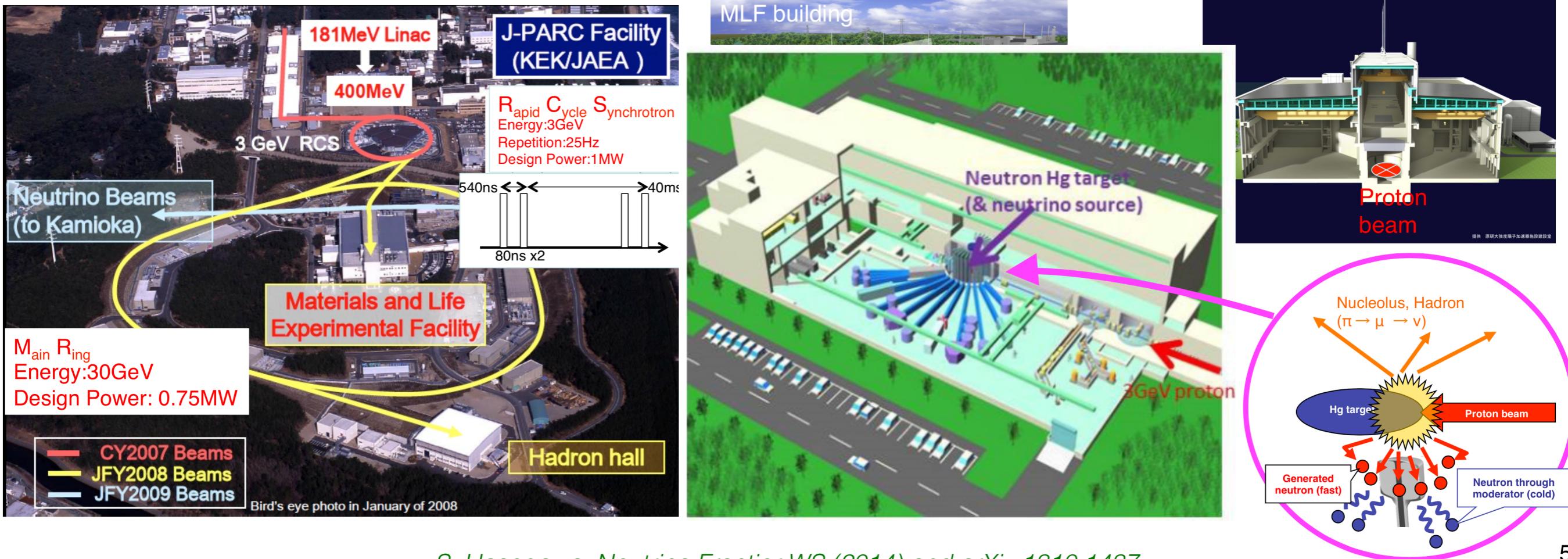
- ▶ Use 3 GeV protons from Rapid Cycle Synchrotron (RCS), 1 MW, 540 ns spill, 25 Hz rep rate, incident on Hg target
 - ▶ 3.0×10^{22} protons/year => $1.0 \times 10^{22} \nu/\text{year}$
- ▶ Gd-loaded liquid scintillator detector

$\pi^+ \rightarrow \mu^+ \nu_\mu$ decay at rest with monochromatic neutrino energy of 30 MeV
 $\mu^- + A \rightarrow \nu_\mu + A$ with end point at 105 MeV On-bunch

$K^+ \rightarrow \mu^+ \nu_\mu$ decay at rest with monochromatic energy of 236 MeV
 $K^+ \rightarrow \mu^+ \pi^0 \nu_\mu$ decay at rest with a end point energy of 215 MeV
 $K^+ \rightarrow e^+ \pi^0 \nu_e$ decay at rest with end point energy at 228 MeV
Small components from π and K decay in flight

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ Off-bunch

If μ^- stop in a light material, μ^- also decay partially by $\mu^- \rightarrow e^+ \bar{\nu}_e \nu_\mu$



S. Hasegawa, Neutrino Frontier WS (2014) and arXiv:1310.1437

SBL Decay-At-Rest - P56@MLF

- **P56 @ J-PARC-MLF (Materials and Life Science Facility), Japan**

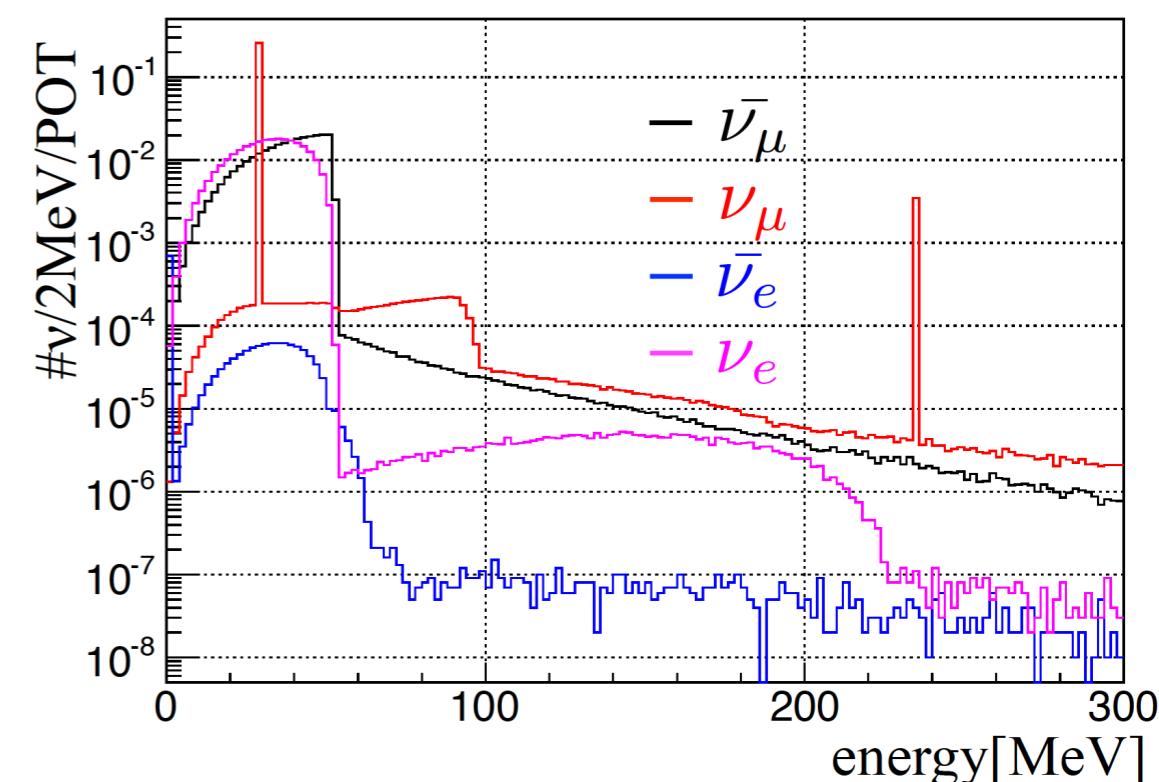
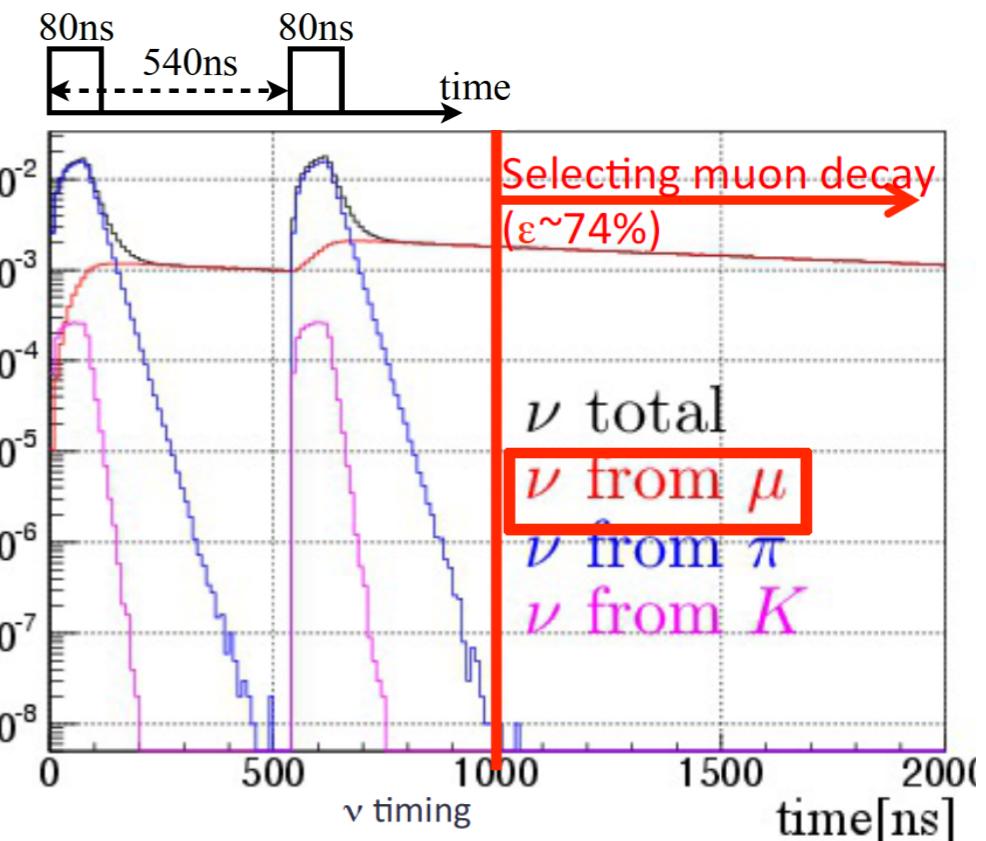
- ▶ Need to select neutrinos from μ^+ decay at rest
 - ▶ μ^+ has long lifetime, so use 1 μs timing cut

- ▶ Energy spectrum of $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ decay is well understood
 - Useful to examine the excess of $\bar{\nu}_e$
 - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation can be searched

- ▶ $\pi^- \rightarrow \mu^-$ decay chain is highly suppressed, 10^{-3} compared to μ^+ , due to π^- capture in nuclei

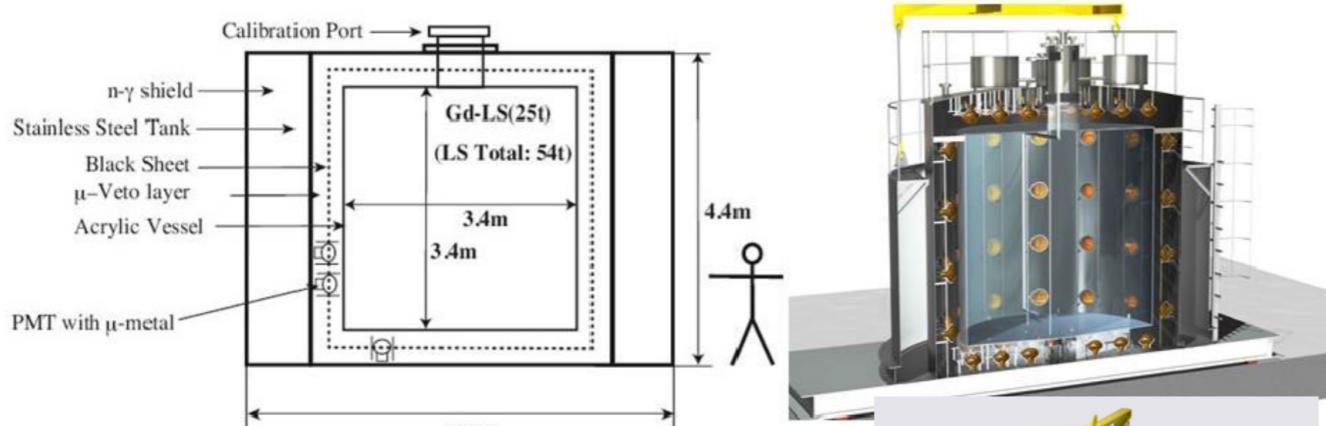
- ▶ Proton energy of J-PARC is 3 GeV, thus π^+/p ratio is higher than LSND (0.8 GeV) by 5-10 times

- ▶ Can also look at ν_μ and ν_e from kaon decays, but need extensive studies of backgrounds



SBL Decay-At-Rest - P56@MLF

- P56 @ J-PARC-MLF (Materials and Life Science Facility), Japan

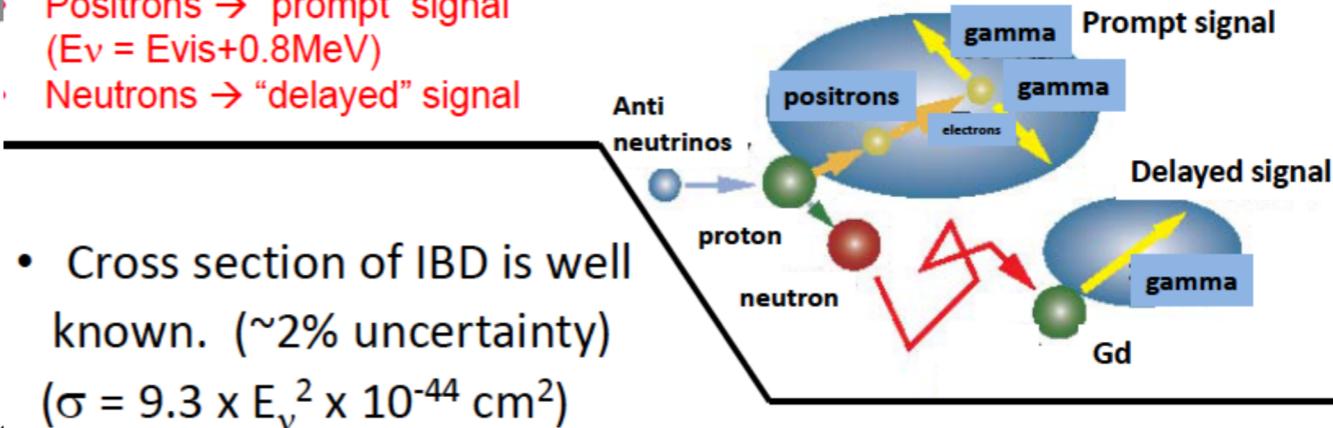


- Detector
→ Gd loading LS 50t
- Schedule
→ It takes two years to construct detector

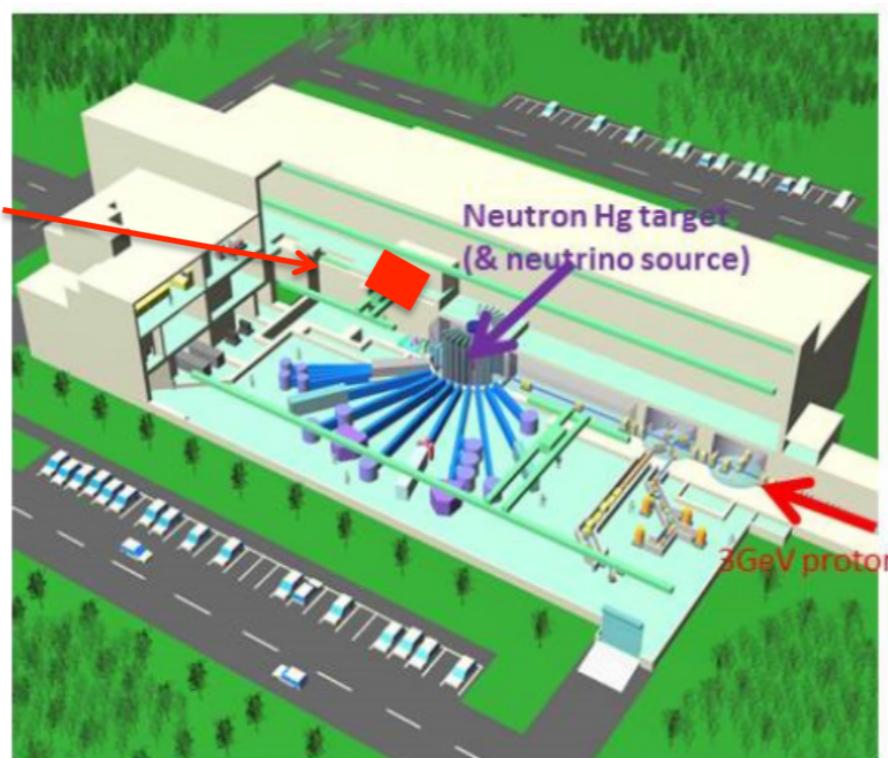


Detector; Liquid scintillator

- Coincidence between positron and neutron signal ($\bar{\nu}_e + p \rightarrow e^+ + n$; Inverse Beta Decay; IBD).
 - Neutrons are captured by Gd, and emit gammas (total $E = 8\text{MeV}$, lifetime; a few $10\text{ }\mu\text{s}$.)
 - Positrons → “prompt” signal ($E_v = E_{vis} + 0.8\text{MeV}$)
 - Neutrons → “delayed” signal
-
- Cross section of IBD is well known. (~2% uncertainty) ($\sigma = 9.3 \times E_\nu^2 \times 10^{-44} \text{ cm}^2$)



Detector
24m base line



SBL Decay-At-Rest - P56@MLF

- P56 @ J-PARC-MLF (Materials and Life Science Facility), Japan

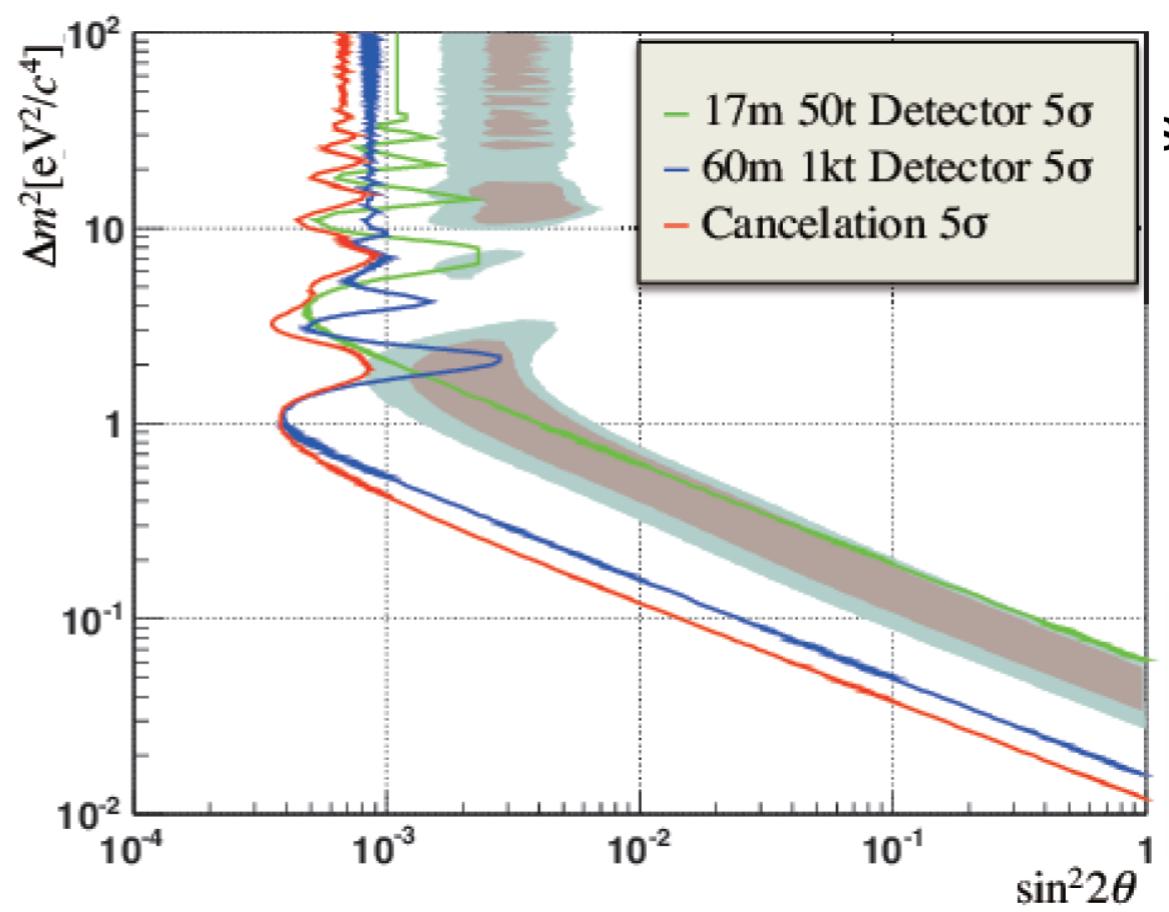
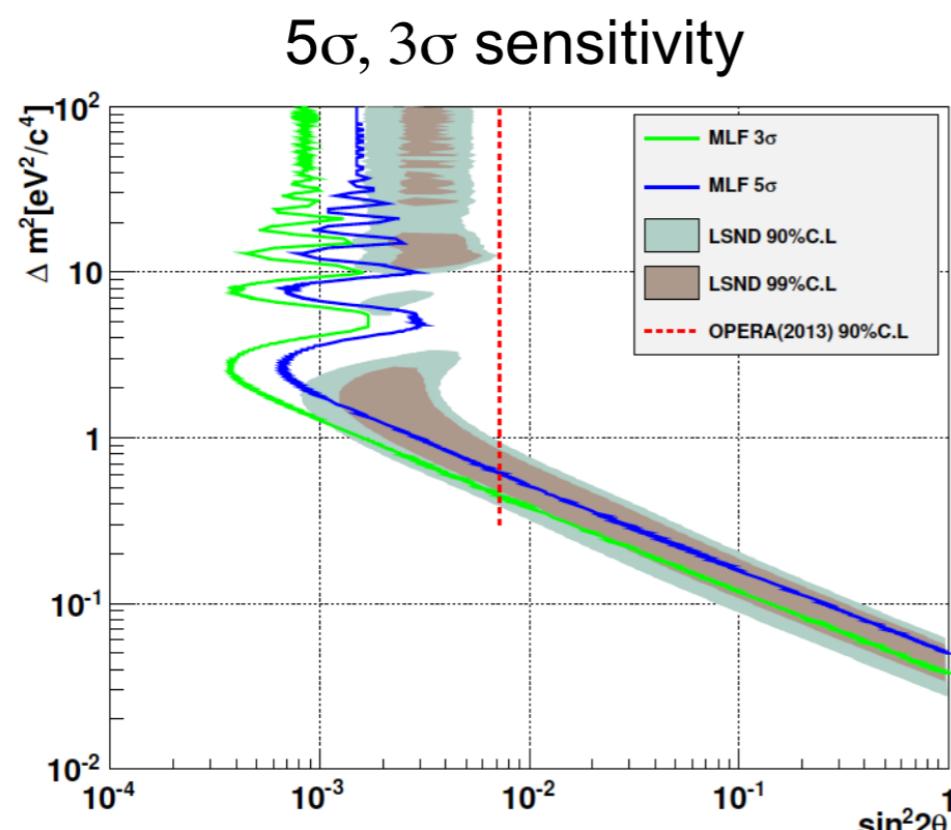
	J-PARC P56	LSND
Beam	pulse	DC
Duty factor and background	30μs/40ms ~10 ⁻³	6% not separate ν from π/ K Neutrino beam cont in Decay-in-flight
detector	LS+Gd	LS + mineral Oil Cherenkov
Coincidence from Inversed Beta Decay	delayed E=8MeV, t=30μs	delayed E=2.2MeV, t=220μs
Beam intrinsic BG	1.7x10 ⁻³	7x10 ⁻⁴
PID	n/e = 1%	n/e = 1%
Signal detection	40%	10-20%
Baseline	24m(candidate location)	30m
Signal event	480/5years	88/6years

► Assumes two 50 ton detectors in phase I

SBL Decay-At-Rest - P56@MLF

- P56 @ J-PARC-MLF (Materials and Life Science Facility), Japan

Source	contents	Number of Event/50t/5y	comments
BG	ν_e from μ^-	237	L=24m
	$^{12}\text{C}(\nu_e, e^-)^{12}\text{N}_{\text{g.s}}$	16	
	Beam fast Neutrons	<13(90%CI UL)	Based on meas.
	Beam fast(cosmic)	37	
	Accidental	32	Based on meas.
signal		480	$\Delta m^2 = 3.0 \sin^2 \theta = 0.003$
		342	$\Delta m^2 = 1.2 \sin^2 \theta = 0.003$

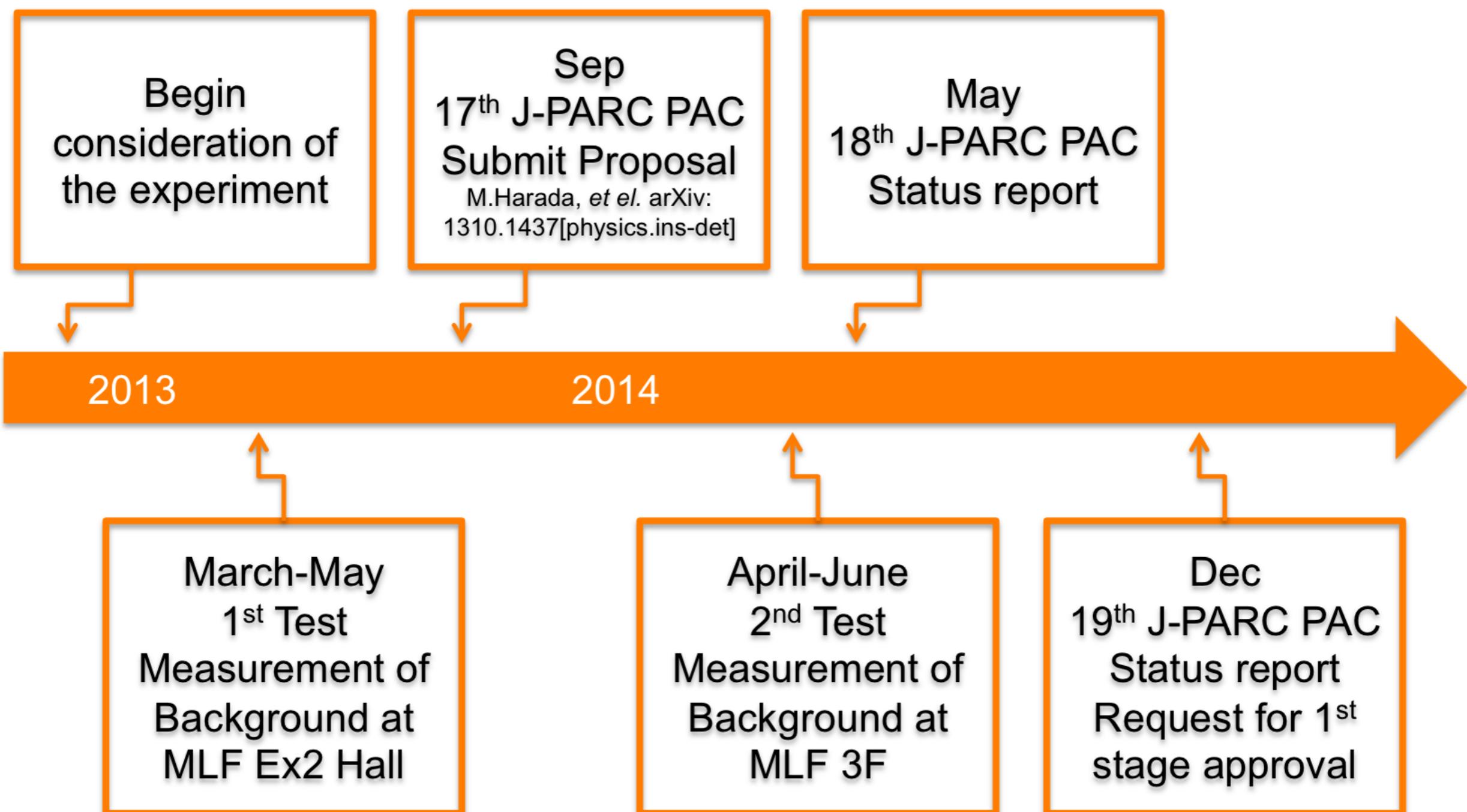


- Signal, Backgrounds and sensitivities over 5 year run in first phase, and sensitivities for later phase with 1 kton detector at 60 m

17

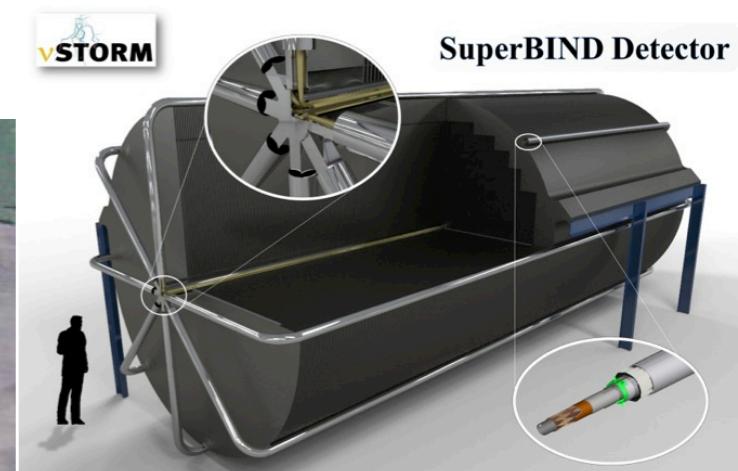
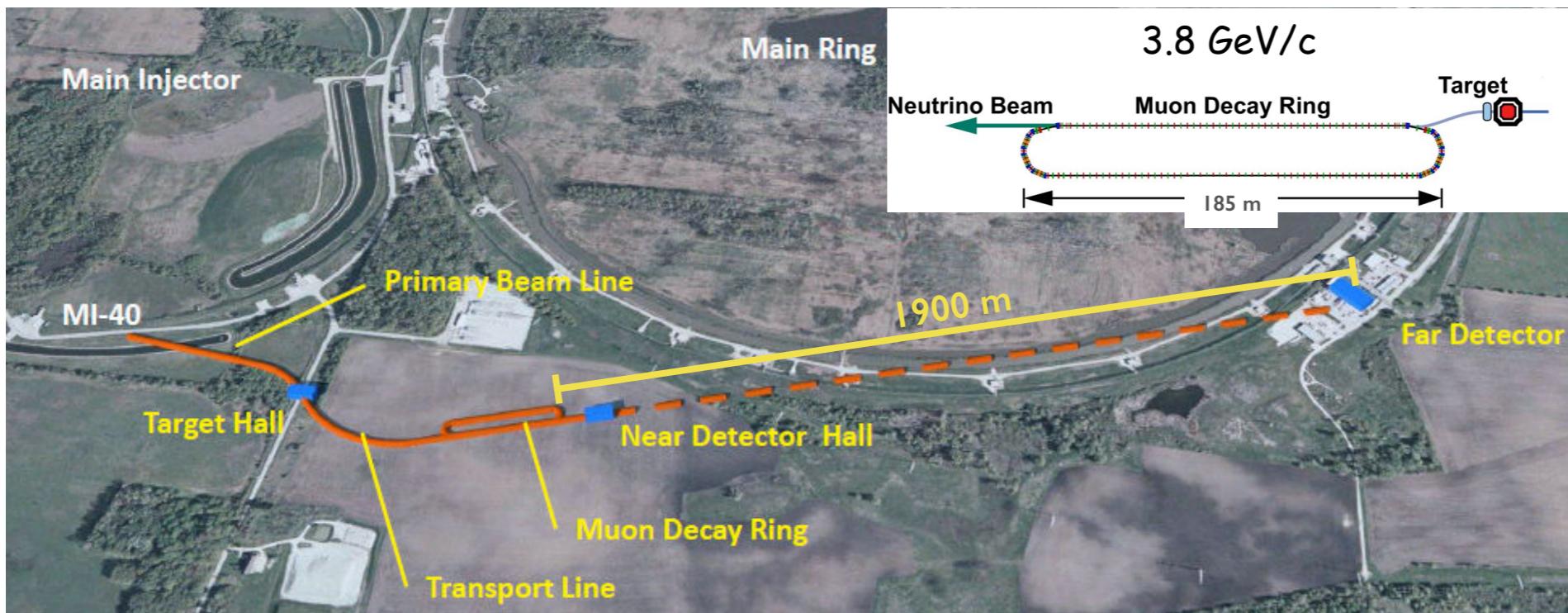
SBL Decay-At-Rest - P56@MLF

- P56 @ J-PARC-MLF (Materials and Life Science Facility), Japan
 - ▶ Estimated cost of \$4.5 million for first phase with two 50 ton detectors

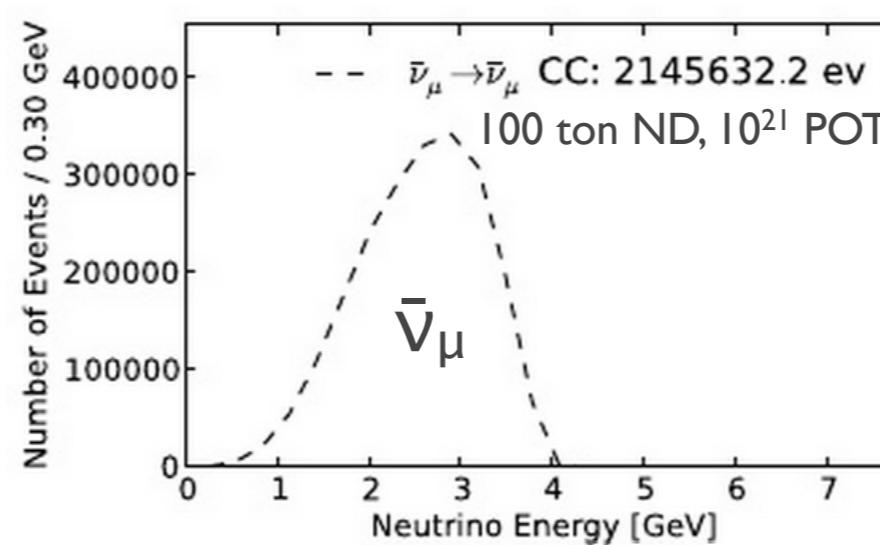
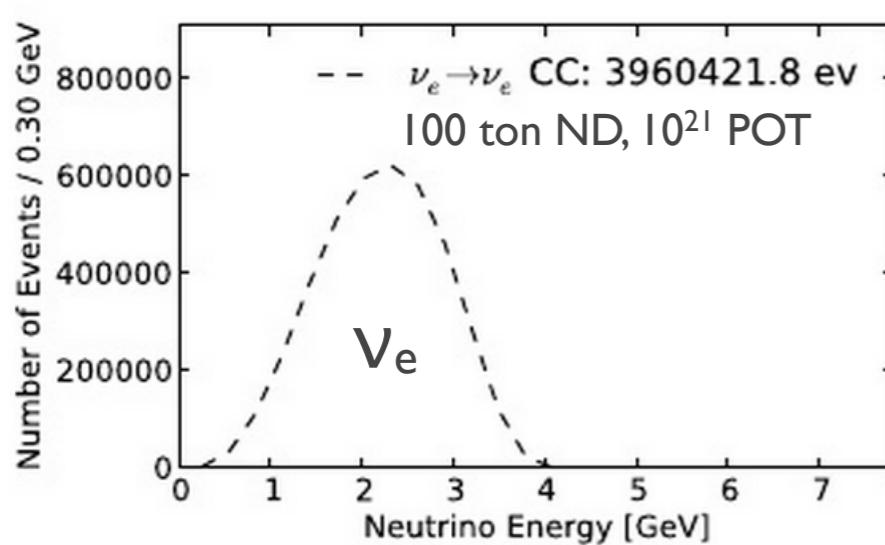


SBL μ Decay-In-Flight - nuSTORM

- nuSTORM (Neutrinos from STORed Muons), to be hosted at Fermilab or CERN
- $\bar{\nu}_\mu, \nu_e, \bar{\nu}_e, \nu_\mu$ beams from muon decay-in-flight in muon storage ring.
- 3.8 GeV/c muons from 100 kW 120 GeV/c proton beam incident in graphite target



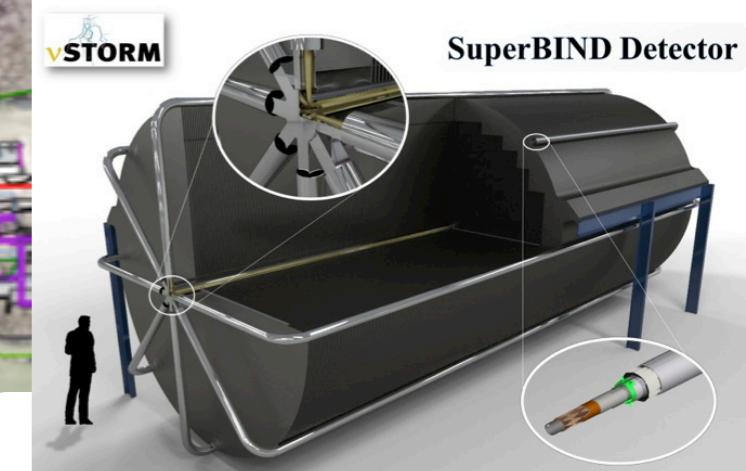
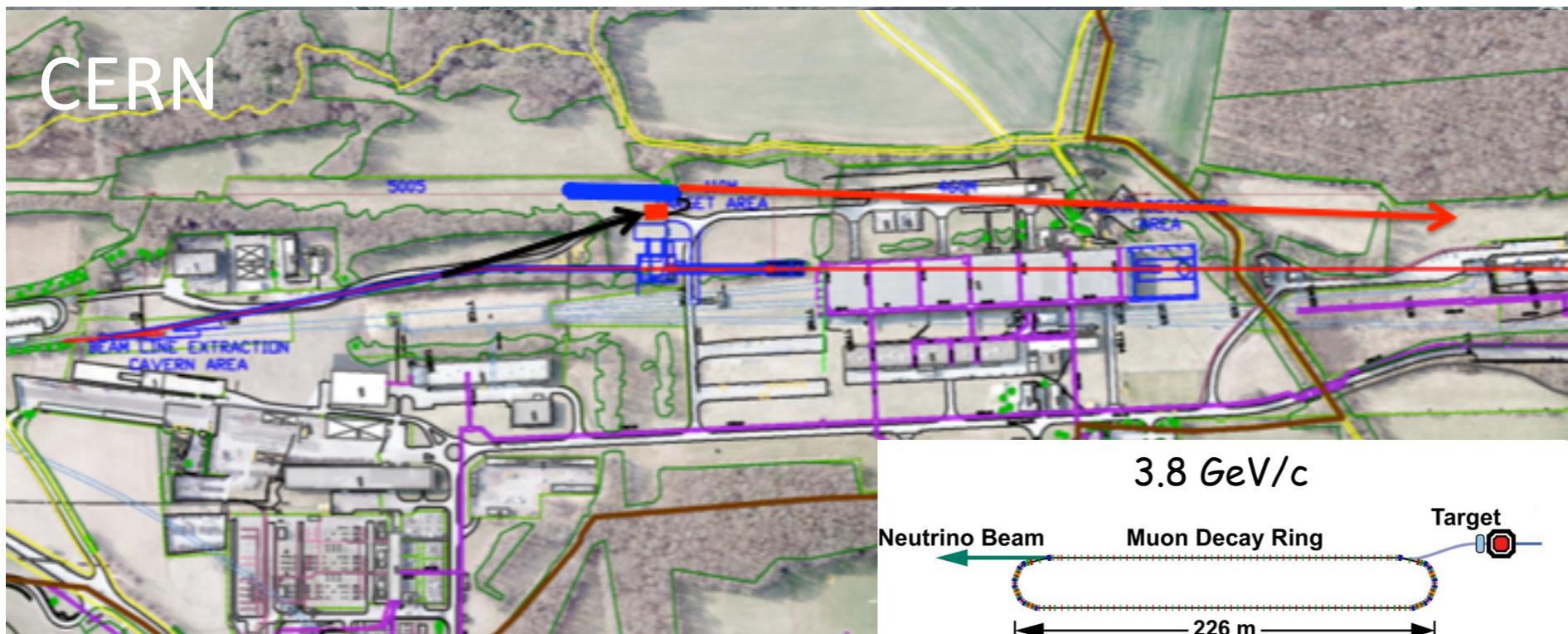
- Proposed FD is a 1.3 kton iron-scintillator tracking calorimeter similar to MINOS ND, but ~ 2.3 T B field is generated by a superconducting transmission line



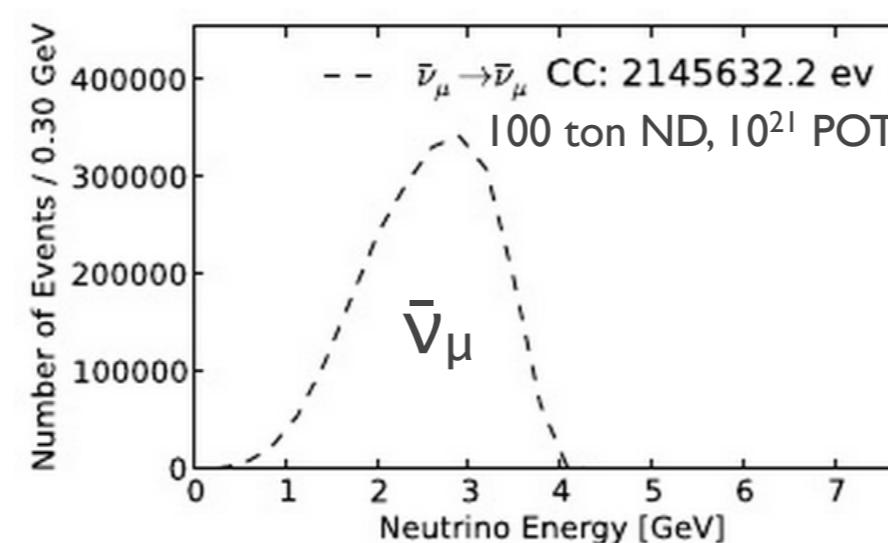
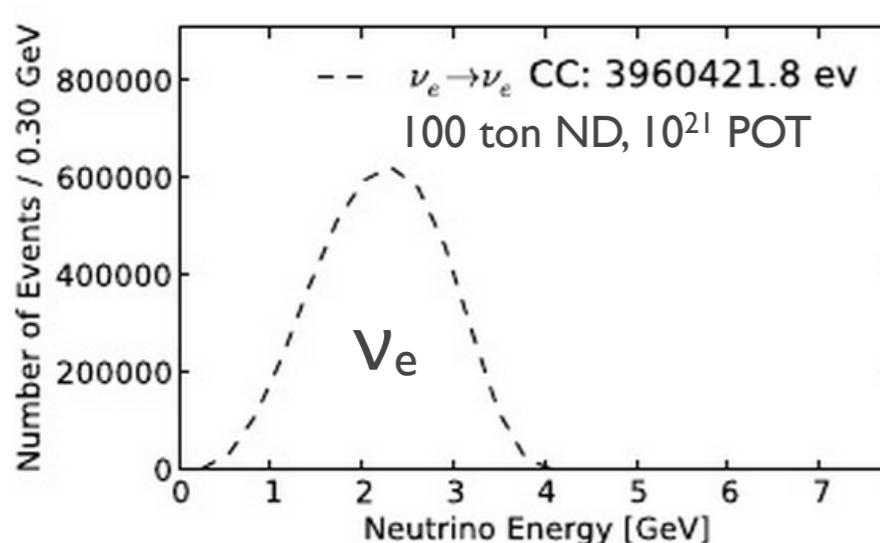
E. Wildner, NUFACt 2014 and arXiv:1402.5250

SBL μ Decay-In-Flight - nuSTORM

- nuSTORM (Neutrinos from STORed Muons), to be hosted at Fermilab or CERN?
- $\bar{\nu}_\mu, \nu_e, \bar{\nu}_e, \nu_\mu$ beams from muon decay-in-flight in muon storage ring. 3.8 GeV/c muons from 100 kW 120 GeV/c proton beam incident in graphite target



- Proposed FD is a 1.3 kton iron-scintillator tracking calorimeter similar to MINOS ND, but ~ 2.3 T B field is generated by a superconducting transmission line



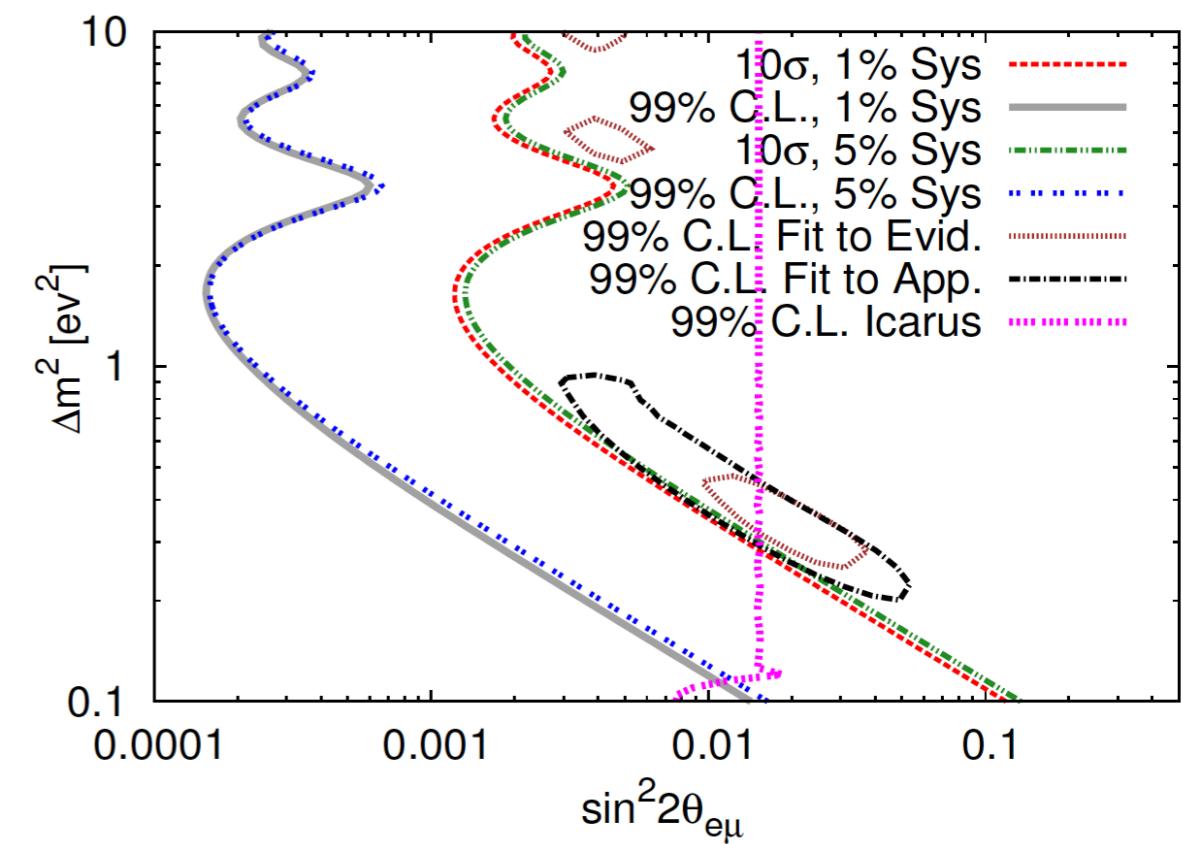
E. Wildner, NUFACt 2014 and arXiv:1402.5250

SBL μ Decay-In-Flight - nuSTORM

- nuSTORM (Neutrinos from STORed Muons), to be hosted at Fermilab or CERN?
 - Experimental setup has access to 8 of 12 possible channels from stored μ^+ or μ^-
 - Using the very large statistics in the CPT invariant mode of LSND, $\nu_e \rightarrow \nu_\mu$, can rule out sterile neutrino allowed regions at 10σ
 - With Near Detector(s), can potentially measure $\nu_e, \bar{\nu}_e$ cross-sections to $\sim 1\text{-}2\%$, which could be essential for future long-baseline experiments

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$	$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$	
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	disappearance
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	appearance (challenging)
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$	appearance (atm. oscillation)
$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	disappearance
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	appearance: “golden” channel
$\nu_e \rightarrow \nu_\tau$	$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$	appearance: “silver” channel

- Project cost $\sim \$300$ million
- Not endorsed by P5
- Pursuing possibility of building nuSTORM at CERN



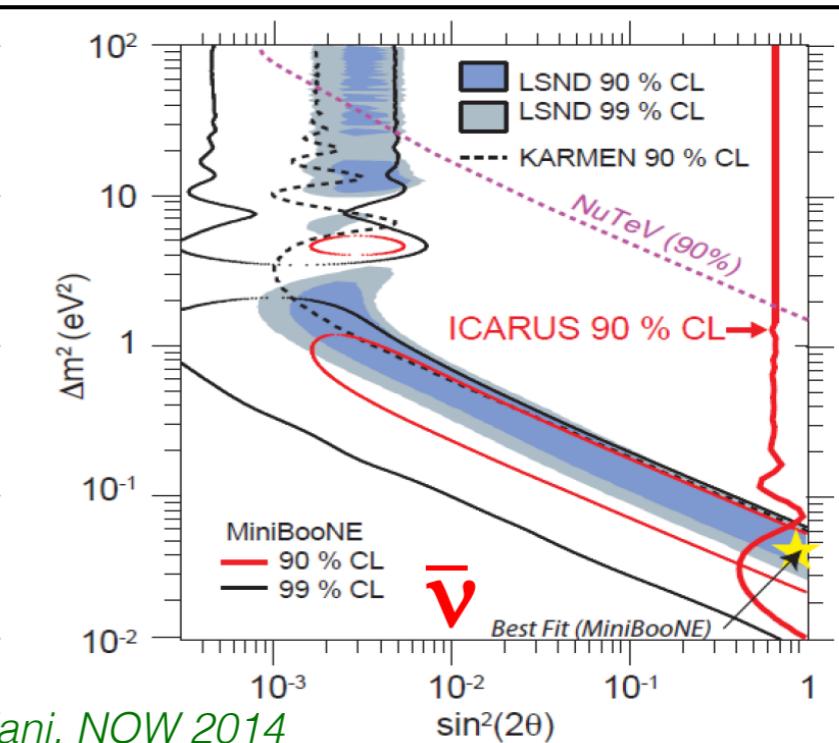
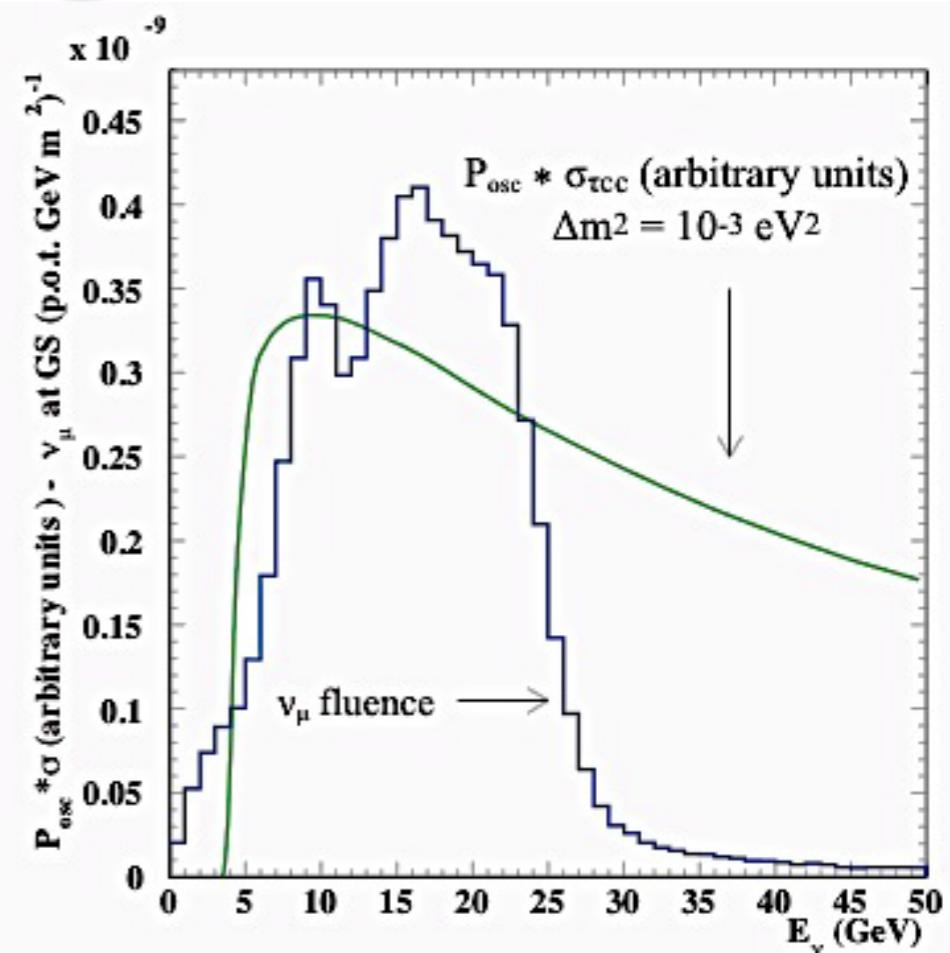
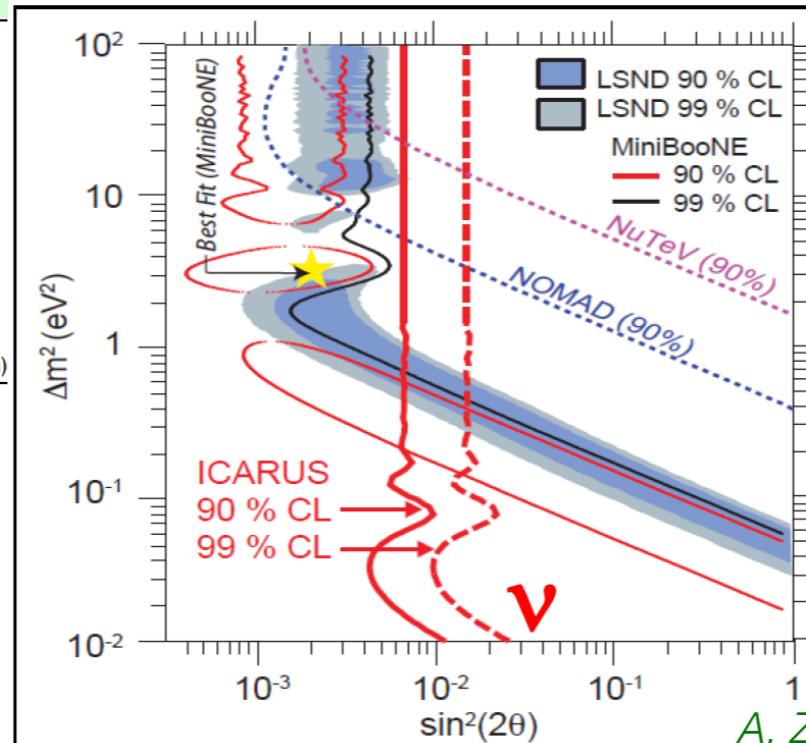
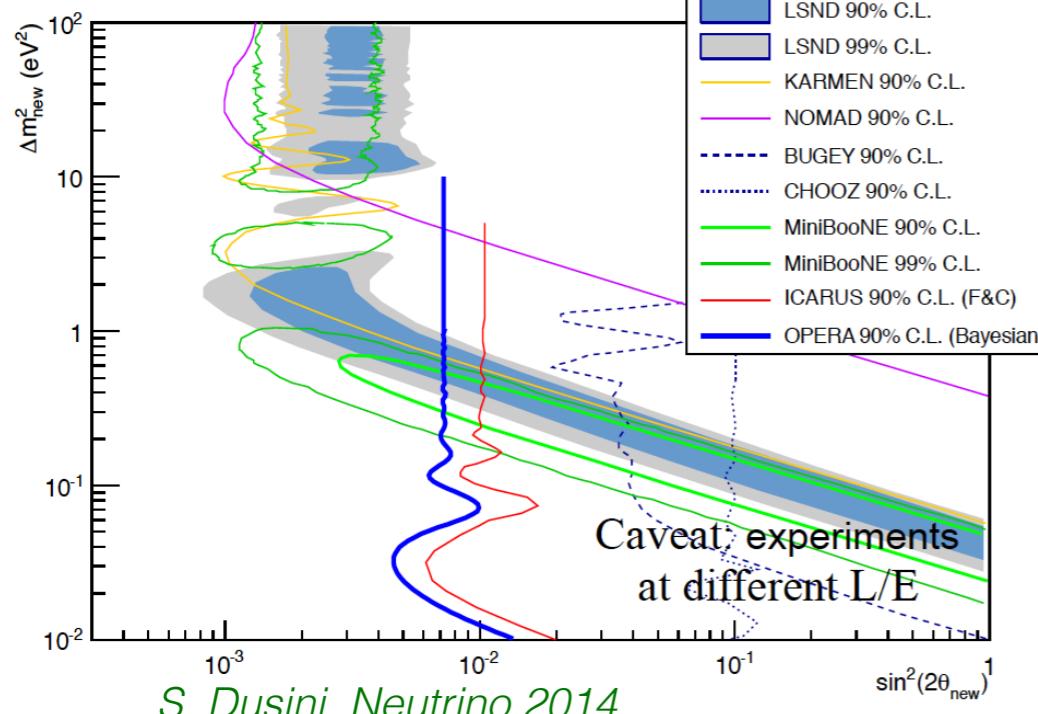
E. Wildner, NUFAC 2014 and arXiv:1402.5250

LBL Decay-In-Flight

- **ICARUS, OPERA @ CERN & LNGS, CH & Italy**

- ▶ Long-baseline experiments can probe large Δm^2 oscillations by looking for anomalous ν_e appearance away from the $\nu_\mu \rightarrow \nu_e$ 3-flavor osc. maximum
- ▶ 1-2% intrinsic beam ν_e contamination
- ▶ OPERA's search includes 50% of full data set. Analysis of complete data set underway

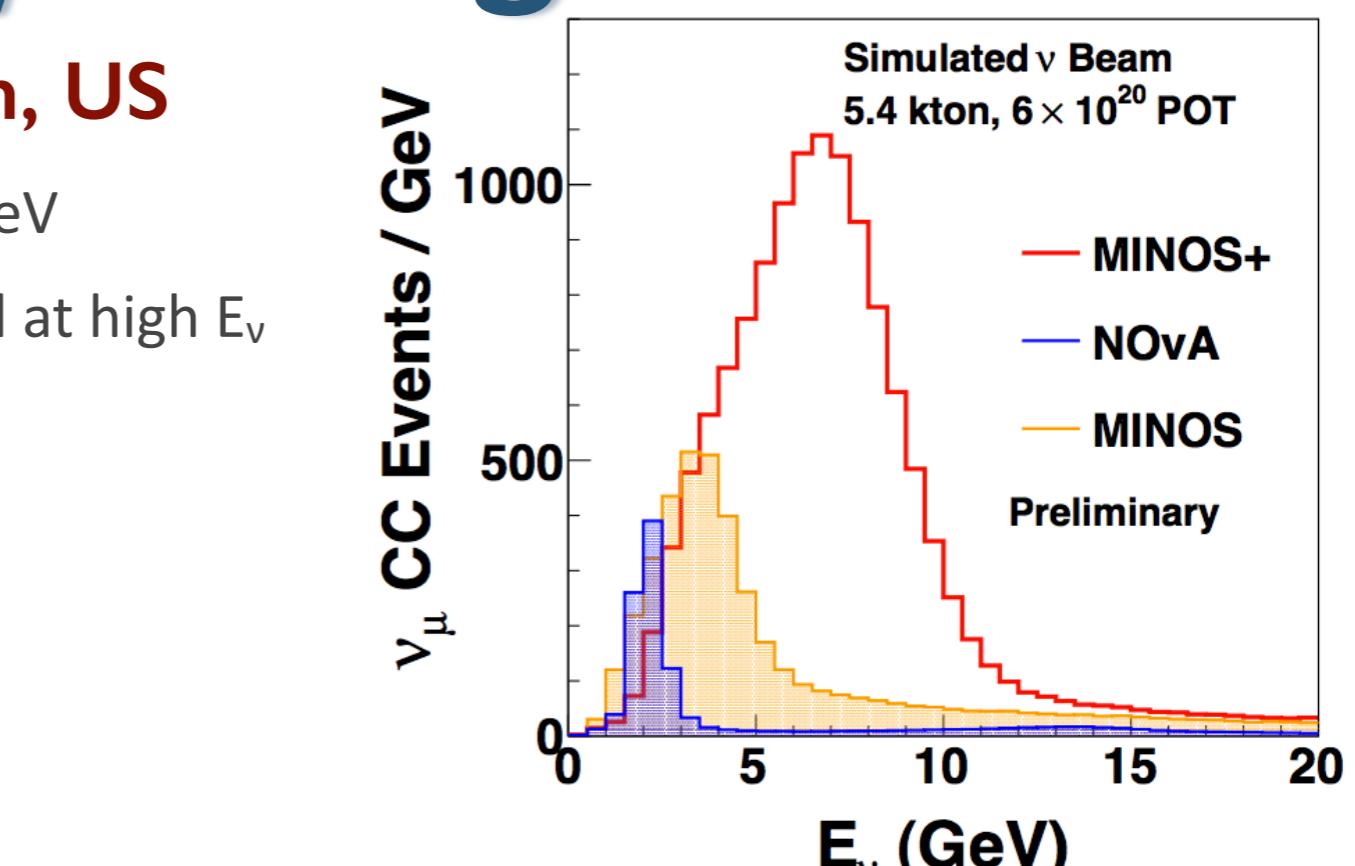
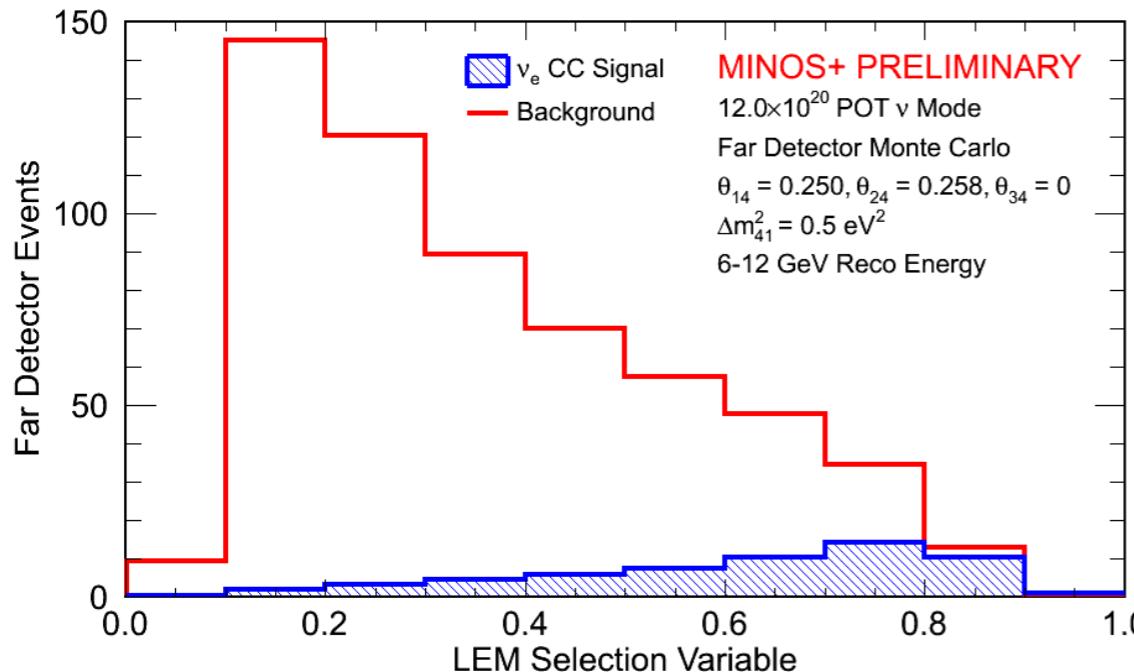
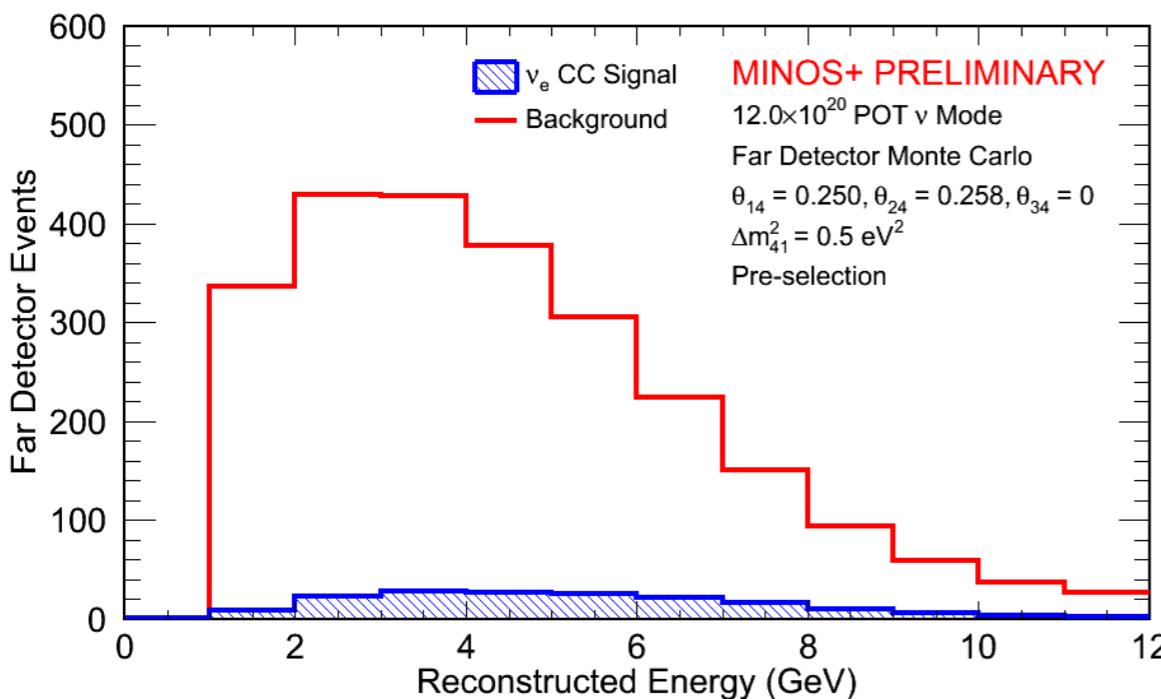
		$E < 20 \text{ GeV}$
Candidate ν_e	19	4
Expected	$19.8 \pm 2.8 \text{ (sys)}$	4.6



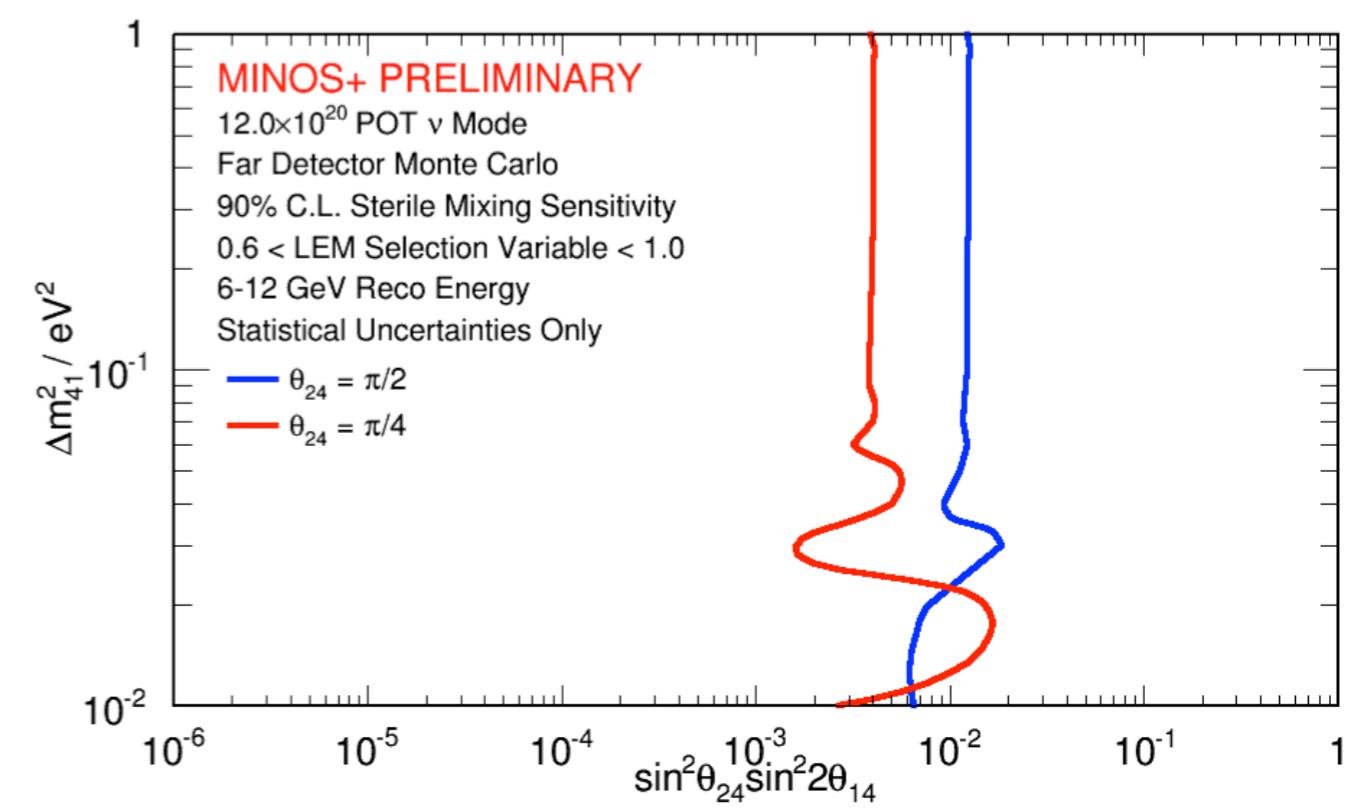
LBL Decay-In-Flight

- **MINOS+ @ Fermilab and Soudan, US**

- ▶ MINOS+ samples NuMI beam peaked at 7 GeV
- ▶ Background falls off more rapidly than signal at high E_ν



A. Schreckenberger, Neutrino 2014



Summary

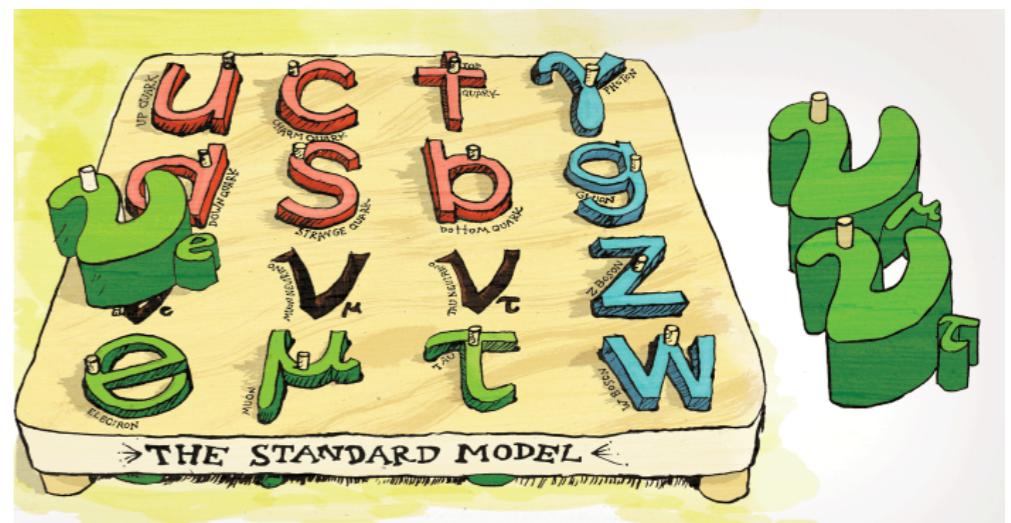
	v Source	Baseline	Host	Cost	Definitive Expt.	Notes
SBL@FNAL	π DIF	110, 470, 600 m	Fermilab	Under Review	Very Likely Yes	Systematics cancellations Access to $\nu, \bar{\nu}$
OscSNS	π, μ DAR	60 m	Oak Ridge National Lab	\$20M	Yes	Most direct test of LSND
P56@MLF	π, μ, K DAR	24 m (Phase I) 60 m (Phase II)	J-PARC	\$4.5M (Phase I)	Only in Phase II	Timeline for phase II?
nuSTORM	μ DIF	1900 m	CERN?	\$300M	Yes	CERN only site left to host
LBL	π DIF	730, 735 km	LNGS, Fermilab	Operations (~\$1M/year)	No	Probes at $\Delta m^2 < 0.1$ eV ²

Conclusions

- ▶ Discovery of light sterile neutrinos would have profound implications in our understanding of neutrino physics and cosmology and open up a new sector in Physics
- ▶ Currently proposed ν_e appearance experiments can confirm or rule out the LSND and MiniBooNE observations, but need to also resolve tension with disappearance measurements
- ▶ Need concurrent ν_e and ν_μ disappearance measurements in both neutrinos and antineutrinos
- ▶ A convincing discovery of light sterile neutrinos will very likely require multiple experiments

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- ▶ Exciting opportunity ahead to get closer to an answer!



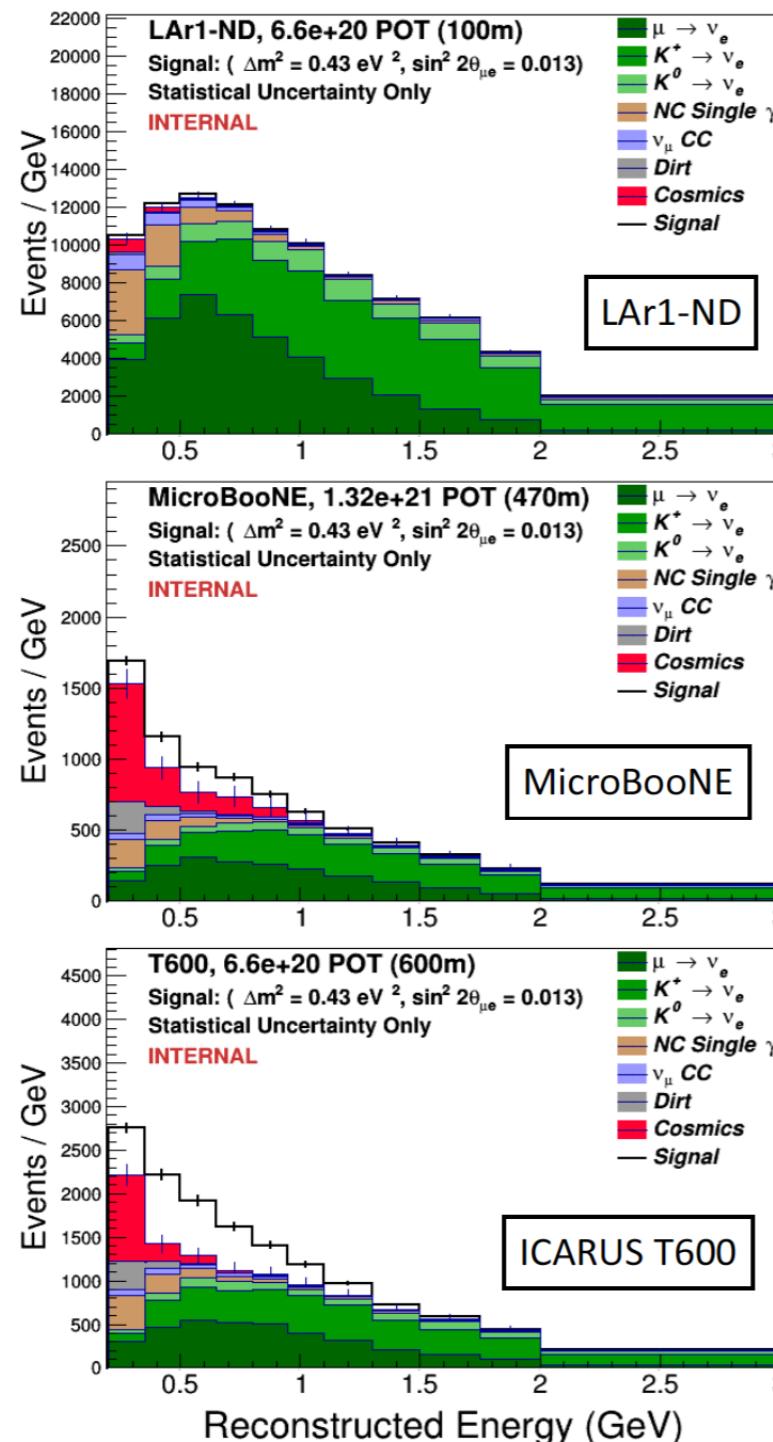
ARE THERE MORE
THAN THREE?
NEUTRINO FLAVORS?

Symmetry Magazine, Feb. 2, 2013

Supplements

SBN Cosmics Rejection

ν_e CC Signal & Background



Here a combination of information from internal light collection and external cosmic tracking arrays are assumed to identify 95% of beam spills contaminated by a cosmic passing near the detector

small loss of data
~1% of beam triggers are rejected

